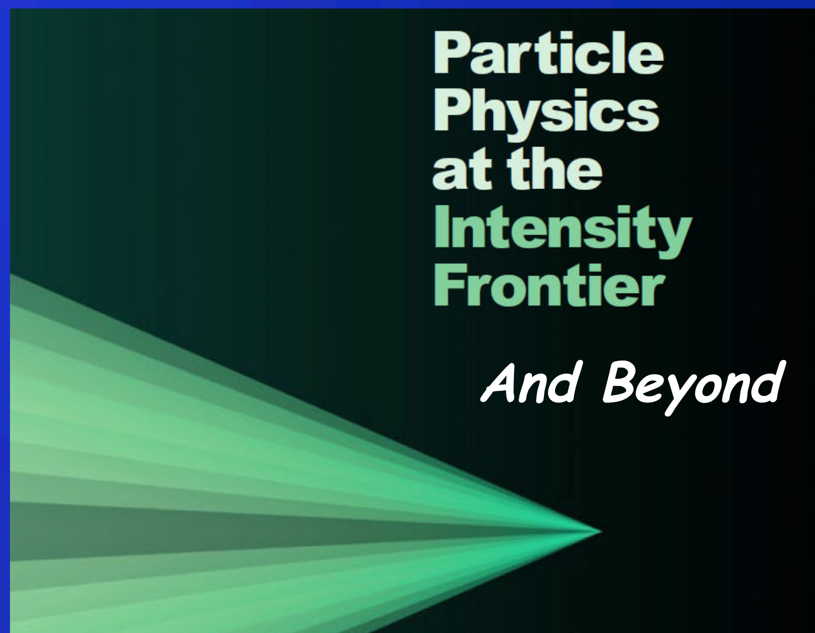
Neutrinos from Stored Muons
νSTORM



ν physics with a μ storage ring

Outline

- Introduction
- Physics motivation
- Current facility design status
- Costing
- Moving forward and Conclusions

Introduction

Introduction

- For over 30 years physicists have been talking about doing ν experiments with νs from μ decay

Well-understood neutrino source:

μ Decay Ring:

$$\mu^+ \rightarrow e^+ \bar{\nu}_\mu \nu_e$$

$$\mu^- \rightarrow e^- \nu_\mu \bar{\nu}_e$$

- Flavor content fully known
  - On the order of rare decay modes (10^{-4})
- "*Near Absolute*" Flux Determination is possible in a storage ring
  - Beam current, polarization, beam divergence monitor, μ_p spectrometer
- Overall, there is tremendous control of systematic uncertainties with a well designed system
- Initially the motivation was high-energy ν interaction physics.

- BUT, so far no experiment has ever been done!

ν physics with a μ storage ring – *Neutrino Factory*

νSTORM

For the past decade+, the focus has been on LBL ν-oscillation physics

$\mu^+ \to e^+ \nu_e \overline{\nu}_\mu$	$\mu^- \to e^- \overline{\nu}_e \nu_\mu$	
$\overline{\nu}_\mu \to \bar{\nu}_\mu$	$\nu_\mu \to \nu_\mu$	disappearance
$\overline{\nu}_\mu \to \bar{\nu}_e$	$\nu_\mu \to \nu_e$	appearance (challenging)
$\overline{\nu}_\mu \to \bar{\nu}_\tau$	$\nu_\mu \to \nu_\tau$	appearance (atm. oscillation)
$\nu_e \to \nu_e$	$\bar{\nu}_e \to \bar{\nu}_e$	disappearance
$\nu_e \to \nu_\mu$	$\bar{\nu}_e \to \bar{\nu}_\mu$	appearance: "golden" channel
$\nu_e \to \nu_\tau$	$\bar{\nu}_e \to \bar{\nu}_\tau$	appearance: "silver" channel

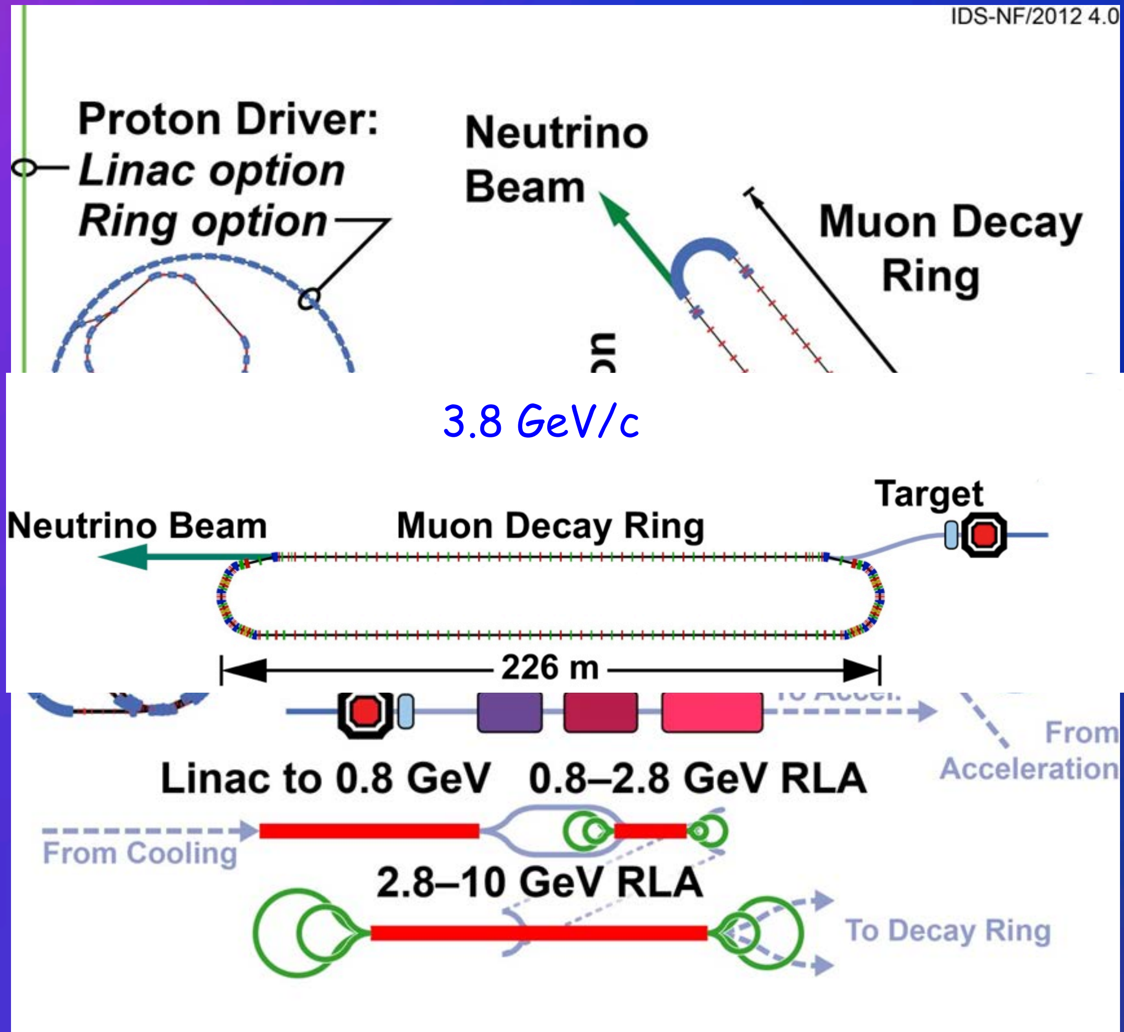
12 channels accessible if E_ν is above the τ threshold

nuSTORM is an affordable μ-based ν beam *"First Step"*

- It is a NEAR-TERM FACILITY
  - Because, technically, we can do it now
- Addresses the SBL, large δm^2 ν-oscillation regime
- Provides a beam for precision ν interaction physics
- Accelerator & Detector technology test bed
  - Potential for intense low energy muon beam
  - Provides for μ decay ring R&D (instrumentation) & technology demonstration platform
  - Provides a ν Detector Test Facility

Status of the Neutrino Factory design: IDS-NF

This is what we want to do near-term: Neutrinos from STORed Muons, νSTORM



This is the simplest implementation of the NF

And DOES NOT Require the Development of ANY New Technology

νSTORM

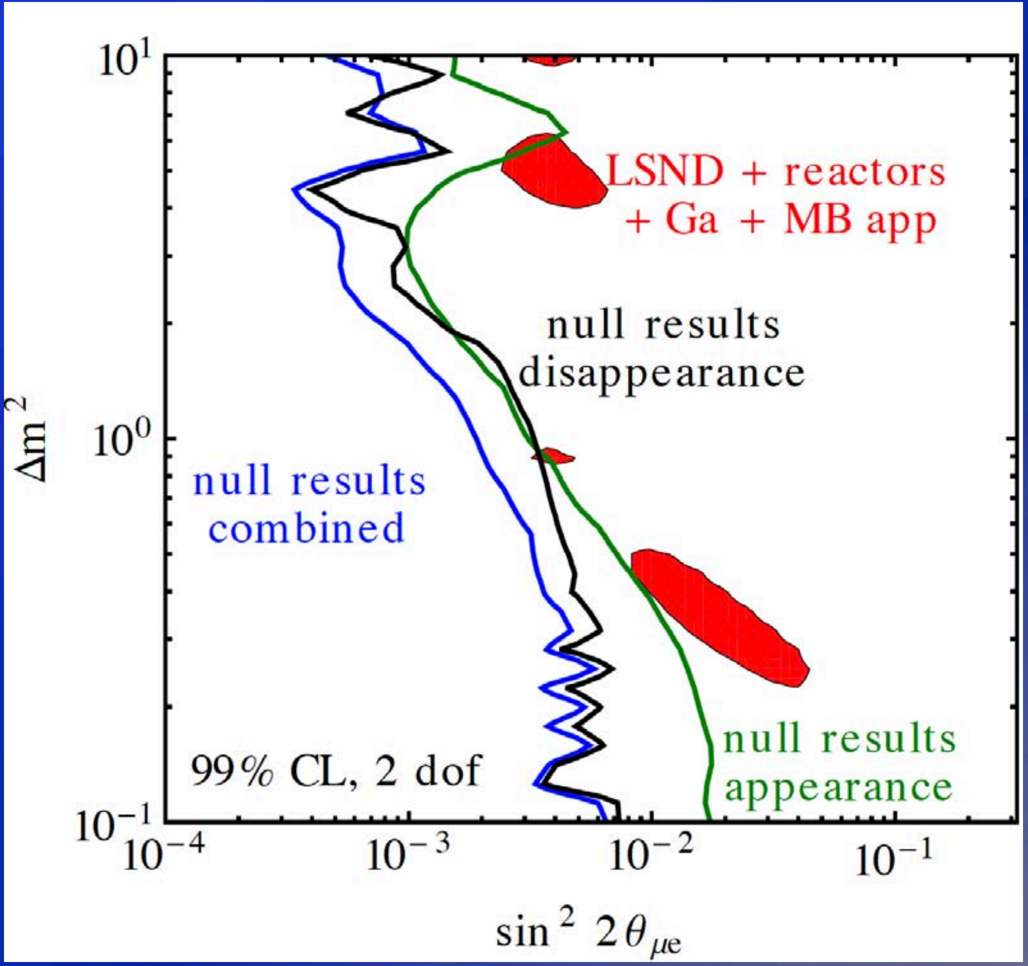
Physics motivation & Theoretical Considerations

Beyond the νSM

Fermilab

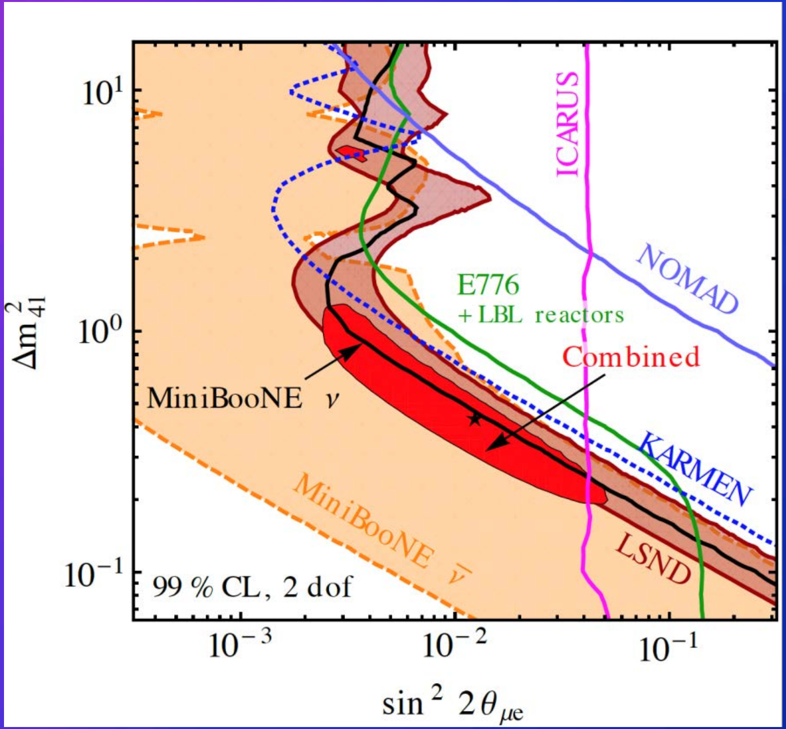
Short-baseline ν oscillation studies

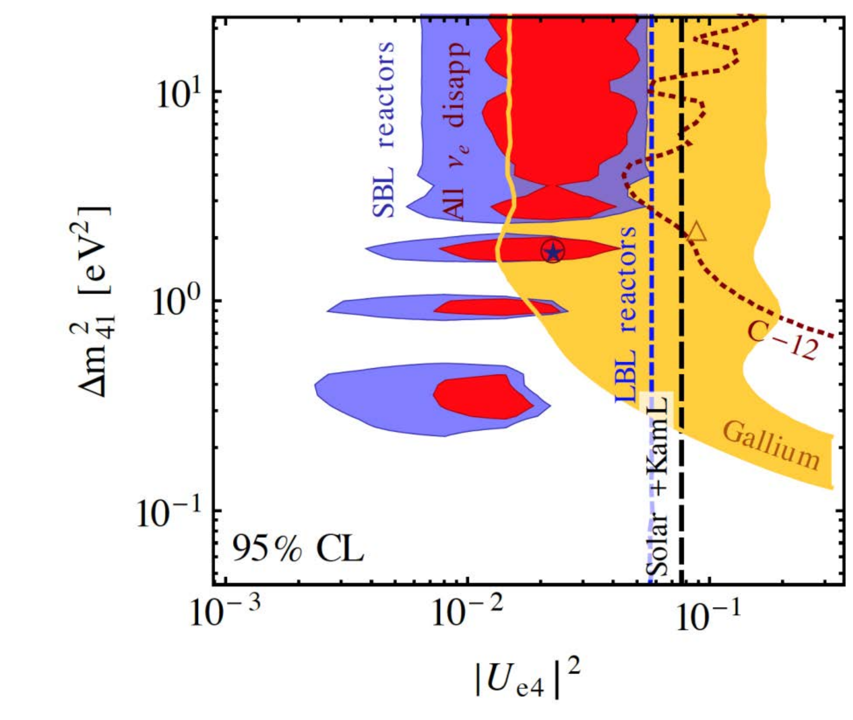
- Sterile neutrinos arise naturally in many extensions of the Standard Model.
  - GUT models
  - Seesaw mechanism for ν mass
  - "Dark" sector
- Usually heavy, but light not ruled out.
- Experimental hints
  - LSND
  - MiniBooNE
  - Ga
  - Reactor "anomaly"



Kopp, Machado, Maltoni & Schwetz: arXiv:1303.3011".

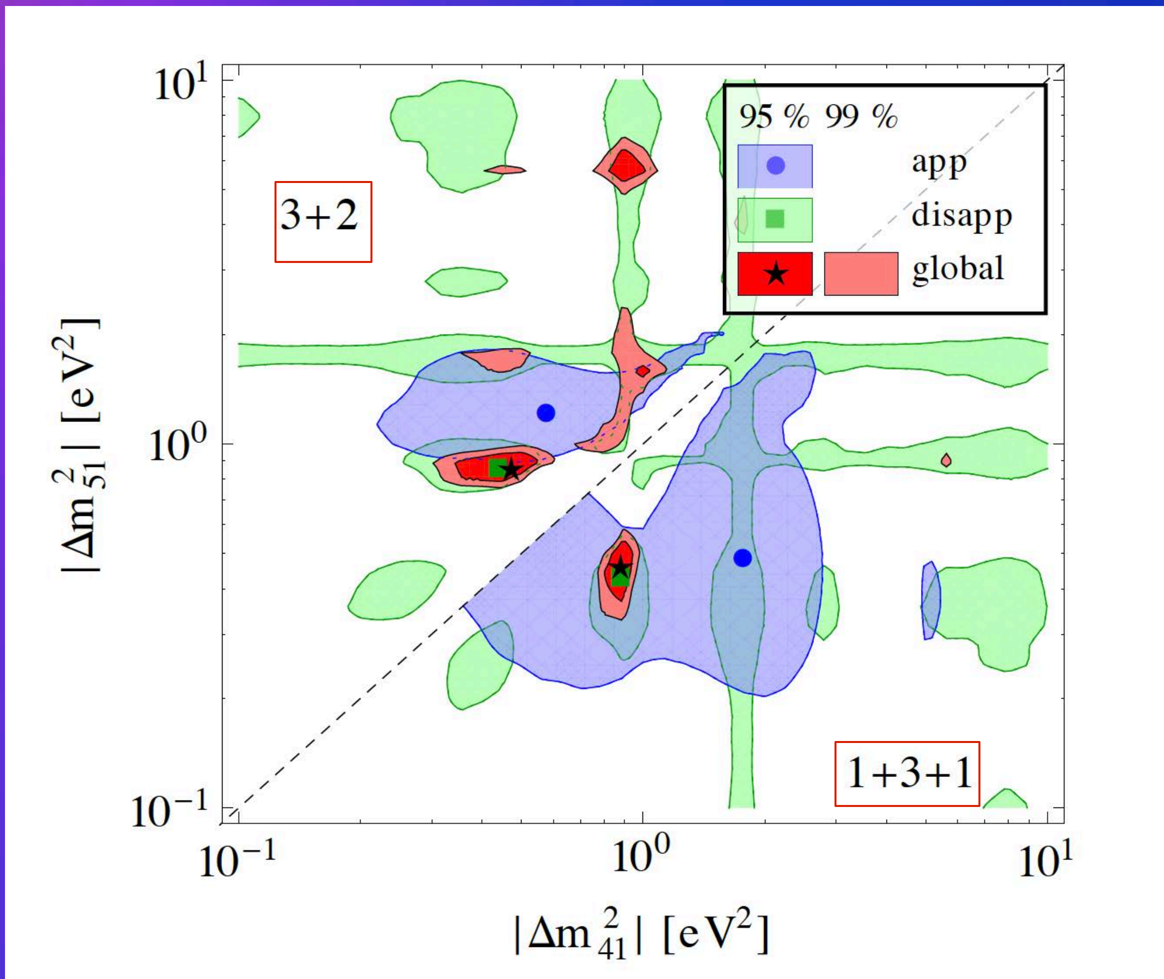
Appearance & disappearance



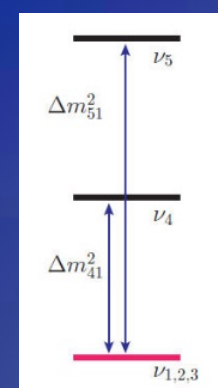


Subsets of appearance and disappearance data are found to be consistent, and it is only when they are combined and when, in addition, exclusion limits on ν_μ disappearance are included, that tension appears.

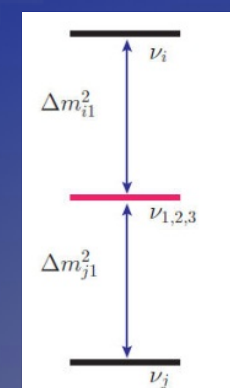
3 + 2 Models



- Fit in 1+3+1 improved over 3+1
- The compatibility of appearance and disappearance data is still low in 1+3+1, at the level of 0.2%.
- $\Sigma_\nu^{min} \approx 3.2$ eV



3+2



1+3+1

Kopp, Machado, Maltoni & Schwetz: arXiv:1303.3011".

Steriles?

- We conclude that, given the current experimental situation:
  - It is impossible to draw firm conclusions regarding the existence of light sterile neutrinos.
  - An experiment searching for short-baseline neutrino oscillations with good sensitivity and well-controlled systematic uncertainties has great potential to clarify the situation.
  - A truly definitive experiment for both the muon appearance and muon disappearance channels is required to reach a convincing conclusion on the existence of light, sterile neutrinos.

ν Interaction Physics

ν Interaction Physics
A partial sampling

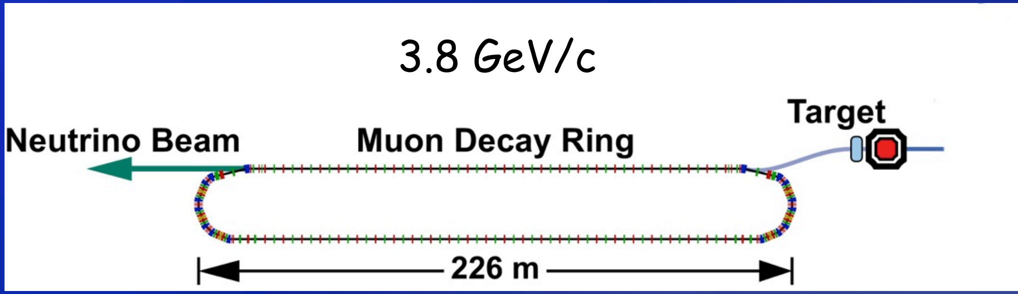
- ν_e and ν_e-bar x-section measurements
  - A UNIQUE contribution from nuSTORM
  - Essentially no existing data
- π^0 production in ν interactions
  - Coherent and quasi-exclusive single π^0 production
- Charged π & K production
  - Coherent and quasi-exclusive single π^+ production
- Multi-nucleon final states
- ν-e scattering
- ν-Nucleon neutral current scattering
  - Measurement of NC to CC ratio
- Charged and neutral current processes
  - Measurement of ν_e induced resonance production
- Nuclear effects
- Semi-exclusive & exclusive processes
  - Measurement of K_s^0, Λ & Λ-bar production
- New physics & exotic processes
  - Test of ν_μ - ν_e universality
  - Heavy ν
  - eV-scale pseudo-scalar penetrating particles

Over 60 topics (thesis) accessible at nuSTORM

The Facility

Baseline

- ~ 100 kW Target Station (designed for 400kW)
  - Assume 120 GeV proton
    - Fermilab PIP era
  - Carbon target
    - Inconel
  - Horn collection after target
- Collection/transport channel
  - Stochastic injection of π
- Decay ring
  - Large aperture FODO
    - Also considering RFFAG
  - Instrumentation
    - BCTs, mag-Spec in arc, polarimeter



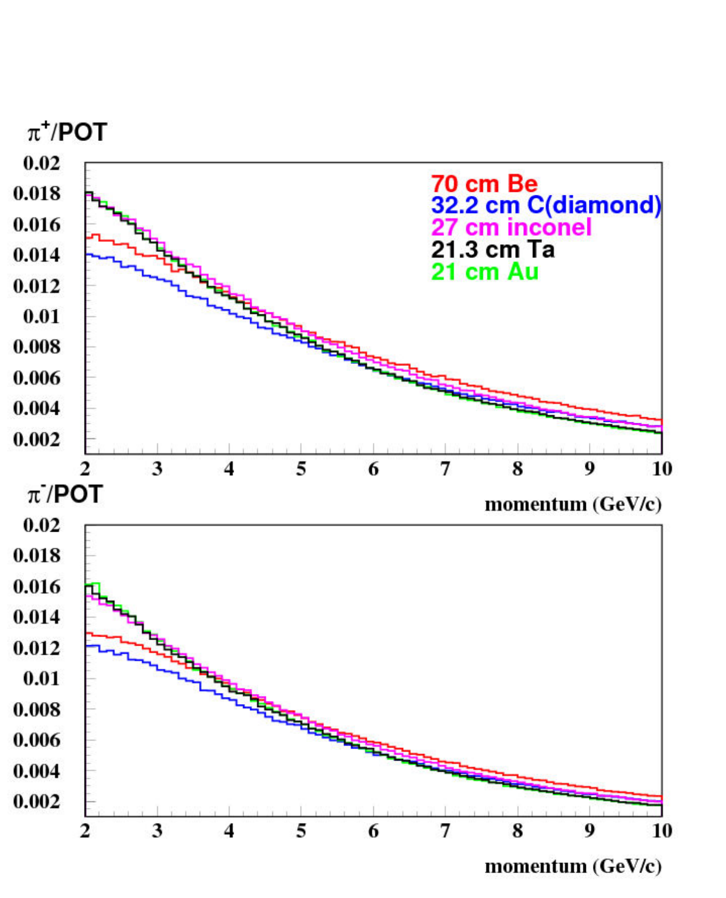
μ-base ν beam: *Oscillation channels*

$\mu^+ \rightarrow e^+ \nu_e \overline{\nu}_\mu$	$\mu^- \rightarrow e^- \overline{\nu}_e \nu_\mu$	
$\overline{\nu}_\mu \rightarrow \bar{\nu}_\mu$	$\nu_\mu \rightarrow \nu_\mu$	disappearance
$\overline{\nu}_\mu \rightarrow \bar{\nu}_e$	$\nu_\mu \rightarrow \nu_e$	appearance (challenging)
$\overline{\nu}_\mu \rightarrow \bar{\nu}_\tau$	$\nu_\mu \rightarrow \nu_\tau$	appearance (atm. oscillation)
$\nu_e \rightarrow \nu_e$	$\bar{\nu}_e \rightarrow \bar{\nu}_e$	disappearance
$\nu_e \rightarrow \nu_\mu$	$\bar{\nu}_e \rightarrow \bar{\nu}_\mu$	appearance: "golden" channel
$\nu_e \rightarrow \nu_\tau$	$\bar{\nu}_e \rightarrow \bar{\nu}_\tau$	appearance: "silver" channel

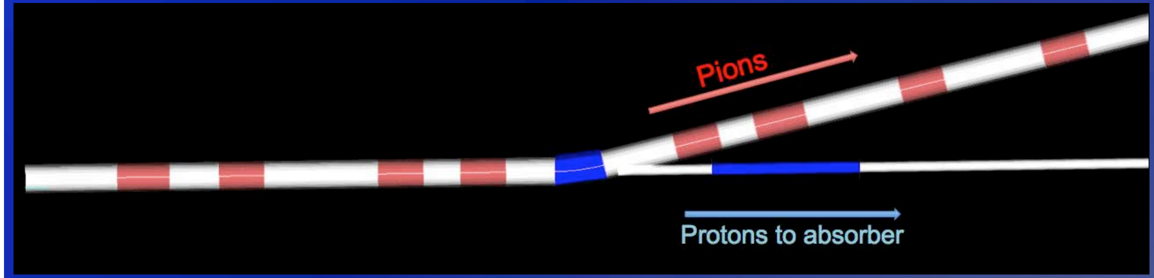
8 out of 12 channels potentially accessible

π Production, Capture & Transport

Sergei Striganov
Ao Liu
Fermilab

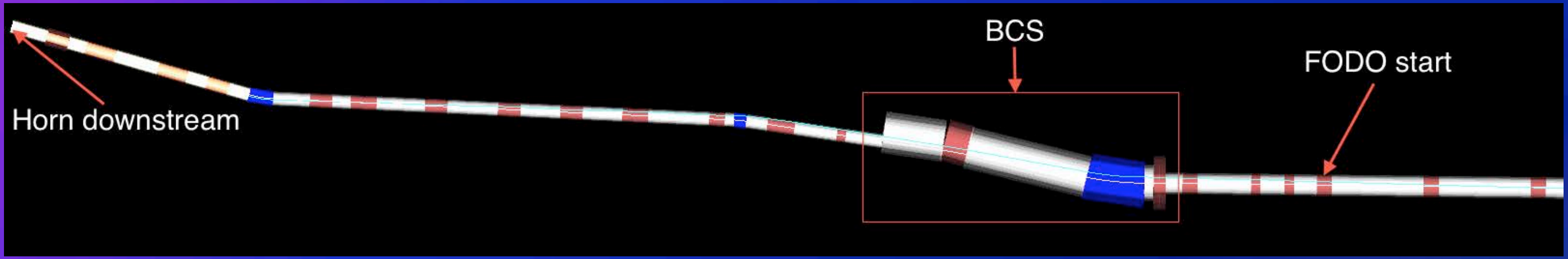


In momentum range
4.5 < 5.0 < 5.5
obtain ≈ 0.09 $\pi^{\pm}$/POT
within decay ring acceptance.
With 120 GeV p & NuMI-style horn 1
Carbon target



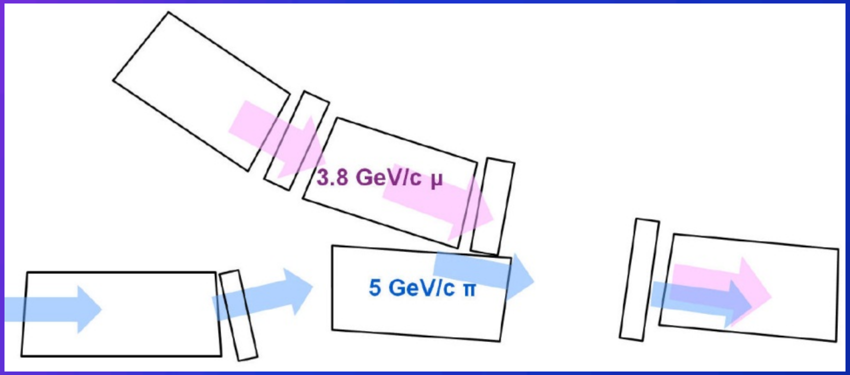
Target/capture optimization ongoing

π Transport & Decay ring

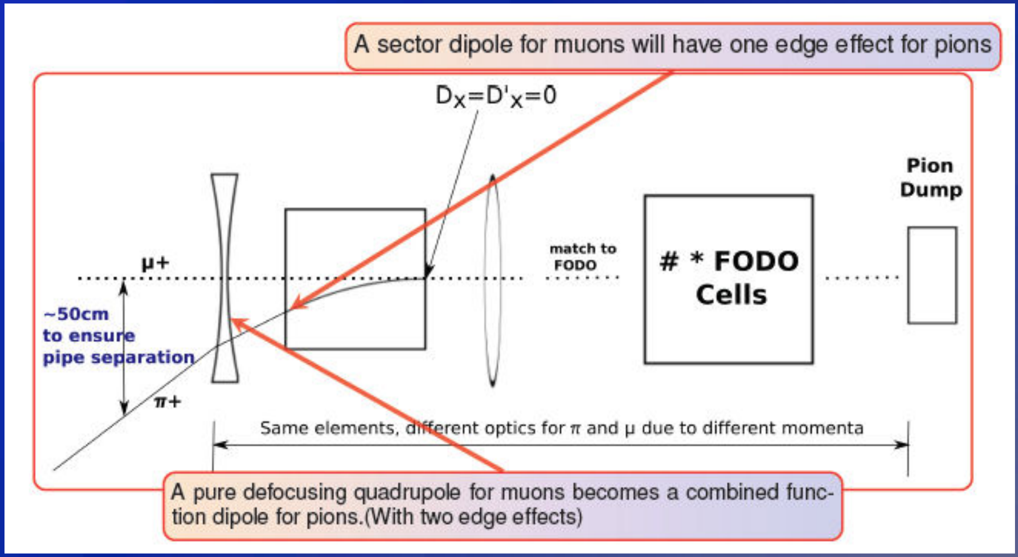


Injection scheme

- π's are on an injection orbit
  - separated by chicane
- μ's are in ring circulating orbit
  - lower p ~3.8 GeV/c
- ~30cm separation between
- Concept works for FODO lattice
  - Now detailed by Ao Liu
- Beam Combination Section (BCS)



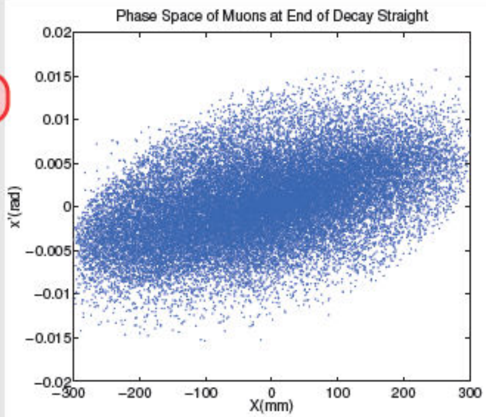
David Neuffer's original concept from 1980



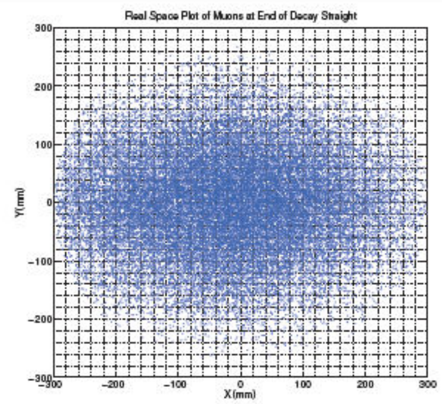
μs at end of first straight

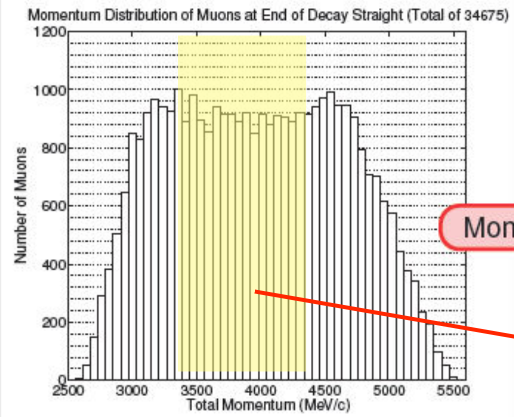
Ao Liu
Fermilab

Phase space plot



Real space plot





Momentum Distribution

8×10^{-3} muons/POT
($3.8 \pm 10\%$) GeV/c
at end of first straight

Muons at the end of decay straight.(Total of 34675 muons. ~ 18% of initial pions.)

(As a comparison, if turn fringe field off –19.7%)

Racetrack FFAG Decay Ring

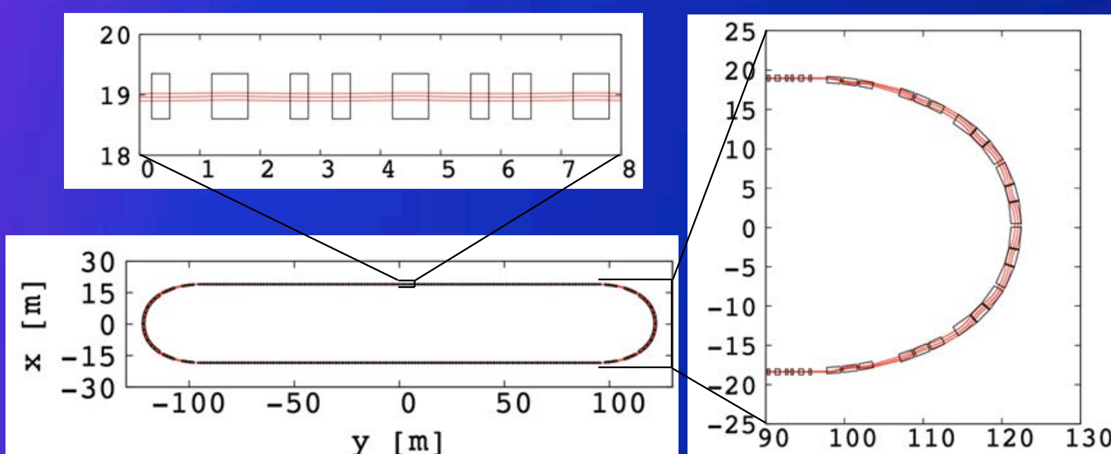
JB Lagrange & Y. Mori: Kyoto
J. Pasternak: Imperial
A. Sato: Osaka

- Scaling FFAGs have special properties, which makes them ideal for large momentum spread and large emittance beams
  - Tune chromaticity is automatically zero
    - Stable optics for very large momentum spread
    - Allows good working point with a large acceptance avoiding dangerous resonances
  - Beta chromaticity is negligible (strictly zero in the current racetrack)
    - Allows to remove the beta beat for off-momentum particles
  - This allows to design the ring with quasi-zero beam loss
    - Good performance for nuSTORM facility!
- Initial FFAG design
  - Confirmed the large acceptance
  - Assumed initially muon injection with a kicker (not preferred currently)
  - Assumed only normal conducting magnets
    - Large ring size
    - Tight space in the arc -> Difficult Stochastic Injection
- Recent FFAG design
  - Based on superferric magnets (up to 3T) in the arc and normal conducting ones in the straight
    - Reduction of the ring size and the cost!
  - Compact Arc (71m)
    - Allows to incorporate the dispersion matching
  - Stochastic injection is now possible
    - Thanks to a smooth dispersion transition and empty drifts in the compact arc.
  - Ring performance with respect to acceptance is very good!

νSTORM

Recent FFAG Decay Ring design

Parameter	FODO	FFAG with normal conducting arcs	FFAG with SC arcs
$L_{Straight}$ (m)	185	240	192
Circumference [m]	480	706	527
Dynamical acceptance A_{dyn}	0.6	0.95	0.95
Momentum acceptance	±10%	±16%	±16%
π/POT within momentum acceptance	0.094	0.171	0.171
Fraction of π decaying in the straight (F_S)	0.52	0.57	0.54
Ratio of $L_{Straight}$ to the ring Circ. (Ω)	0.39	0.34	0.36
$A_{dyn} \times \pi/POT \times F_S \times \Omega$	0.011	0.031	0.033



Layout of the FFAG Decay Ring with SC Arc

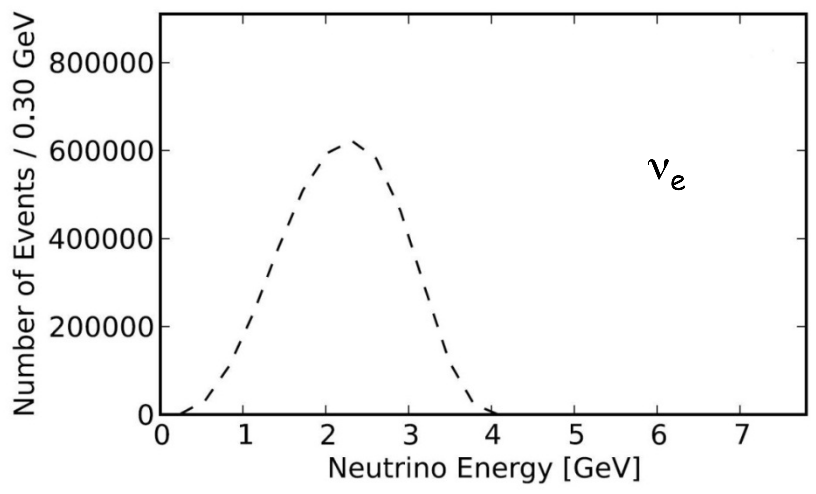
nuSTORM's Physics Reach

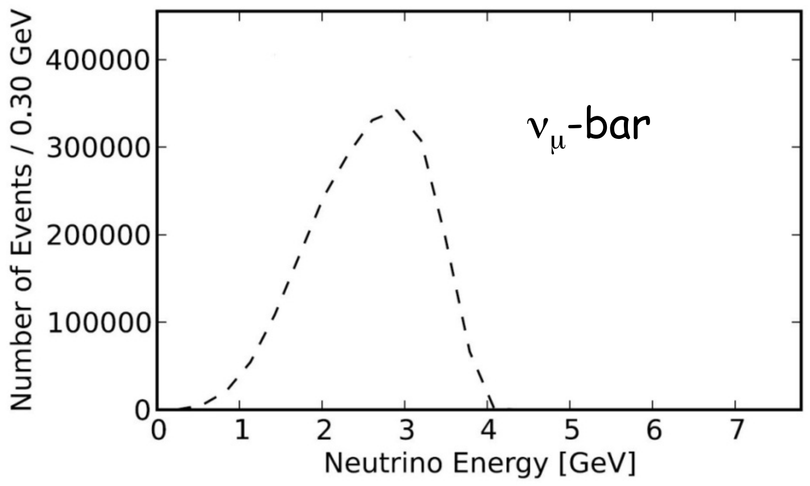
Assumptions

- N_μ = (POT) X (π/POT) X μ/π X $A_{dynamic}$ X Ω
  - 10^{21} POT @ 120 GeV integrated exposure
  - 0.1 π/POT
  - Muons/POT at end of first straight (8 X 10^{-3})
    - =(π/POT) X (μ/π) within the 3.8 ± 10% GeV/c momentum acceptance
  - $A_{dynamic}$ = 0.6 (FODO)
    - Fraction of muons surviving 100 turns
  - Ω = Straight/circumference ratio (0.39) (FODO)
- This yields ≈ 1.9 X 10^{18} useful μ decays

Note: nuSTORM will be limited to 10^{20} POT/yr

E_ν spectra (μ^+ stored)





Event rates/100T at ND hall 50m from straight with μ^+ stored

Channel	N_{evts}
$\bar{\nu}_\mu$ NC	844,793
ν_e NC	1,387,698
$\bar{\nu}_\mu$ CC	2,145,632
ν_e CC	3,960,421

SBL oscillation searches

Appearance

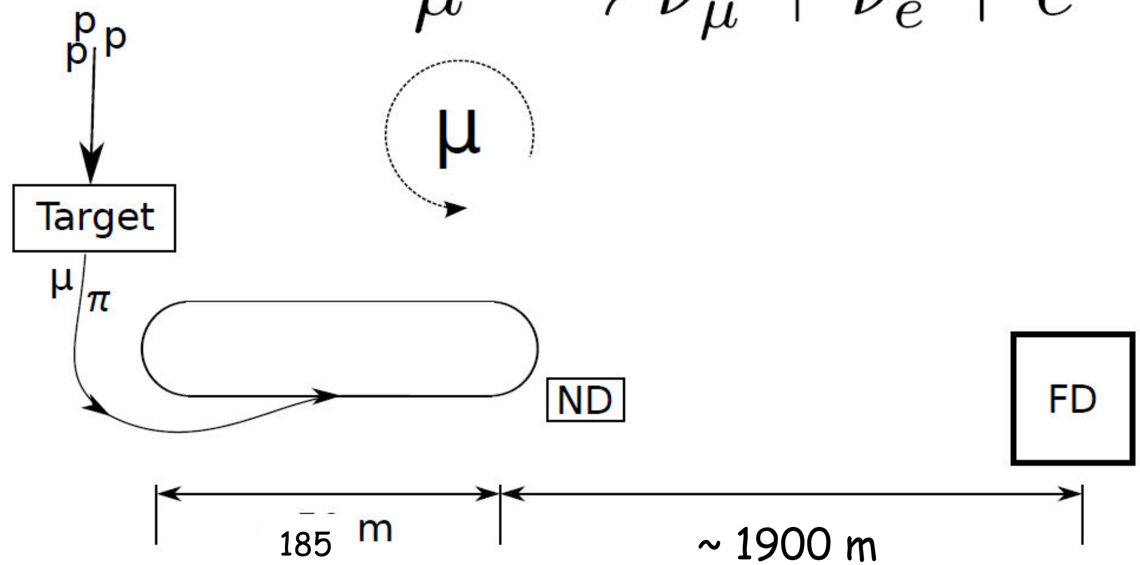
The Golden channel

νSTORM

Experimental Layout

Chris Tunnell
Oxford*

$$\mu^+ \rightarrow \bar{\nu}_\mu + \nu_e + e^+$$



Appearance-only (though disappearance good too!)

$$Pr[e \rightarrow \mu] = 4|U_{e4}|^2|U_{\mu4}|^2 \sin^2(\frac{\Delta m^2_{41} L}{4E})$$

Appearance Channel:

$\nu_e \rightarrow \nu_\mu$

Golden Channel

Must reject the "wrong" sign μ with great efficiency

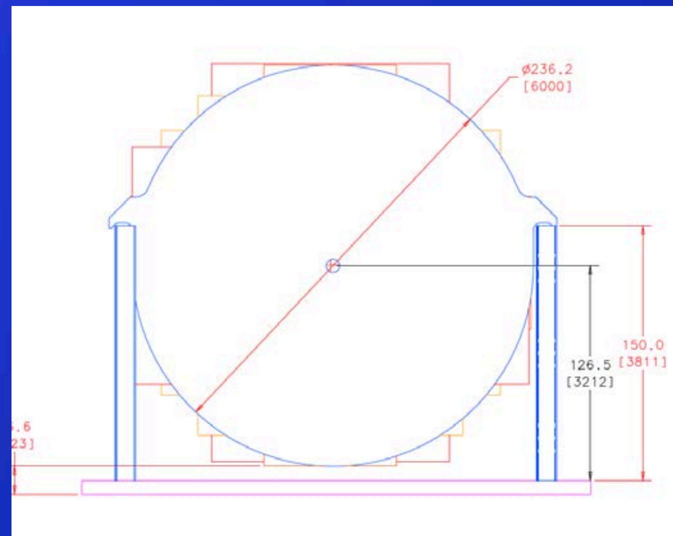
Why $\nu_\mu \rightarrow \nu_e$ Appearance Ch. not possible

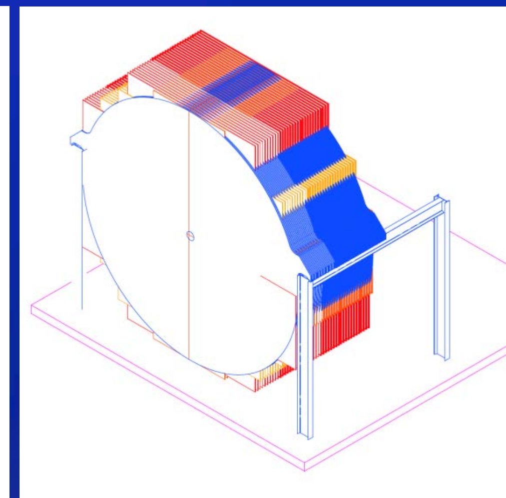
* Now at NIKHEF

Baseline Detector

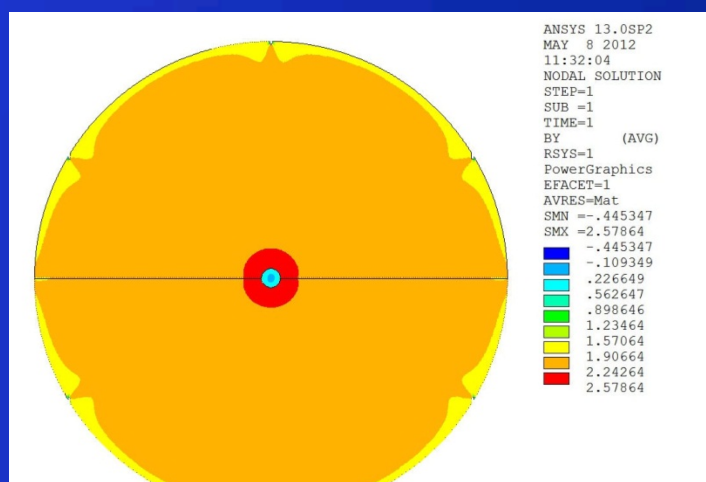
Super B Iron Neutrino Detector: SuperBIND

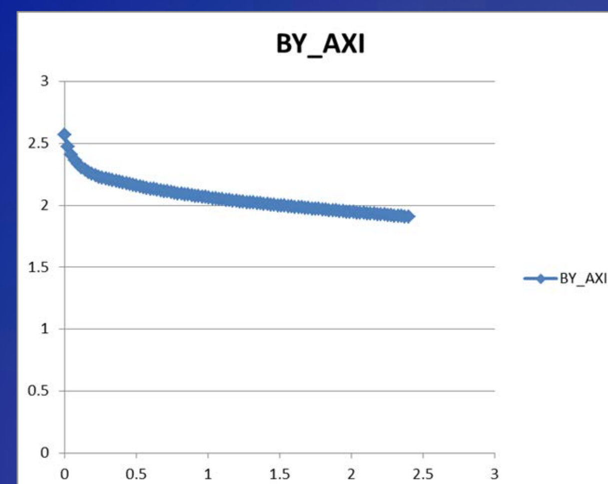
- Magnetized Iron
  - 1.3 kT
    - Following MINOS ND ME design
    - 1.5 cm Fe plate
    - 6 m diameter
  - Utilize superconducting transmission line concept for excitation
    - Developed 10 years ago for VLHC
    - ITER
  - Extruded scintillator +SiPM



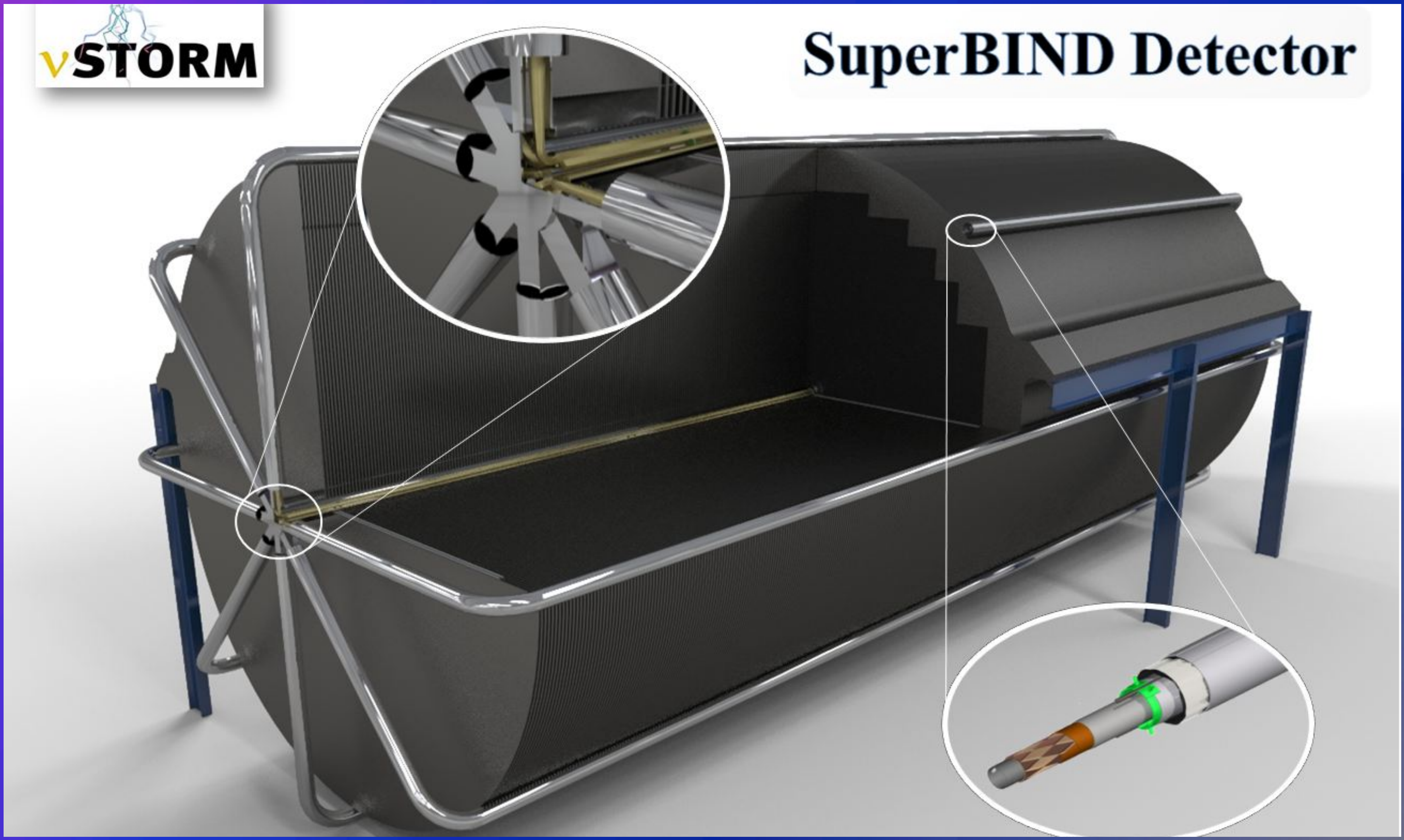


20 cm hole for central cryostat





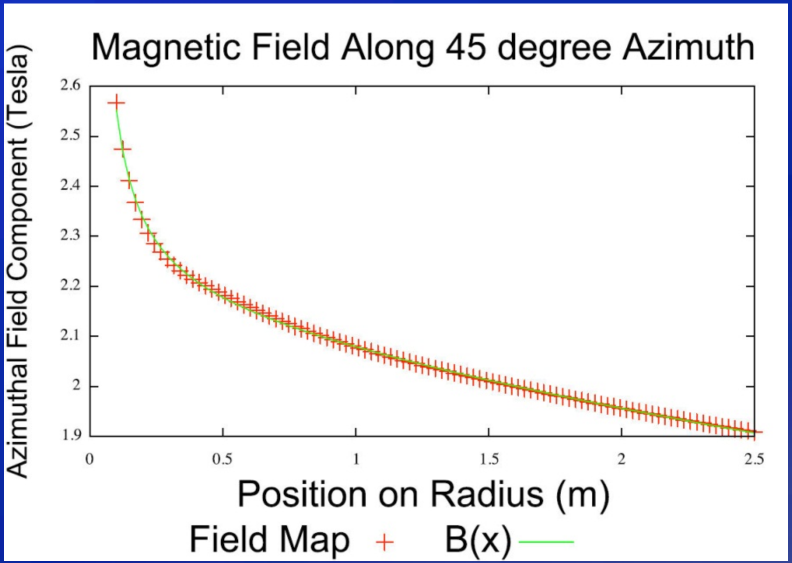
SuperBIND



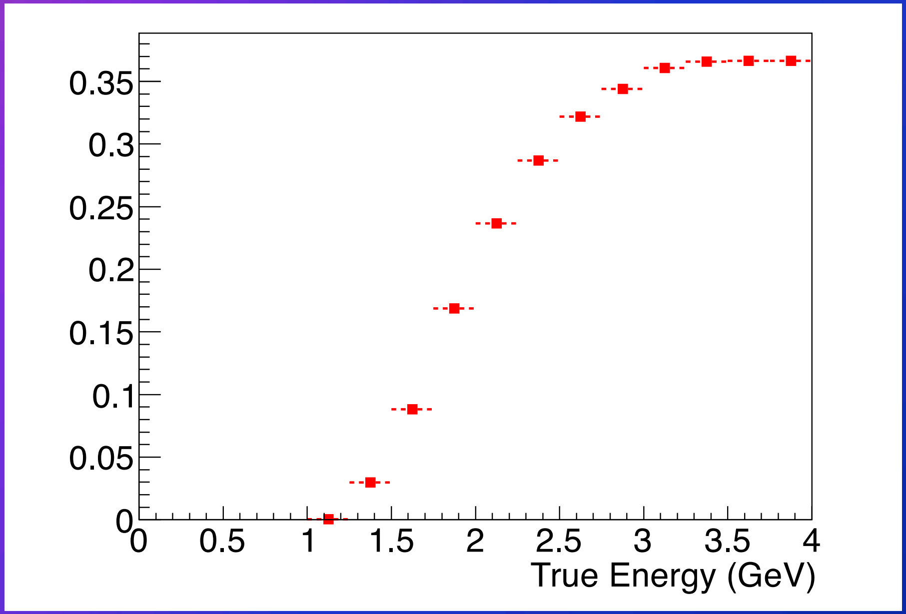
Simulation – ν_μ appearance

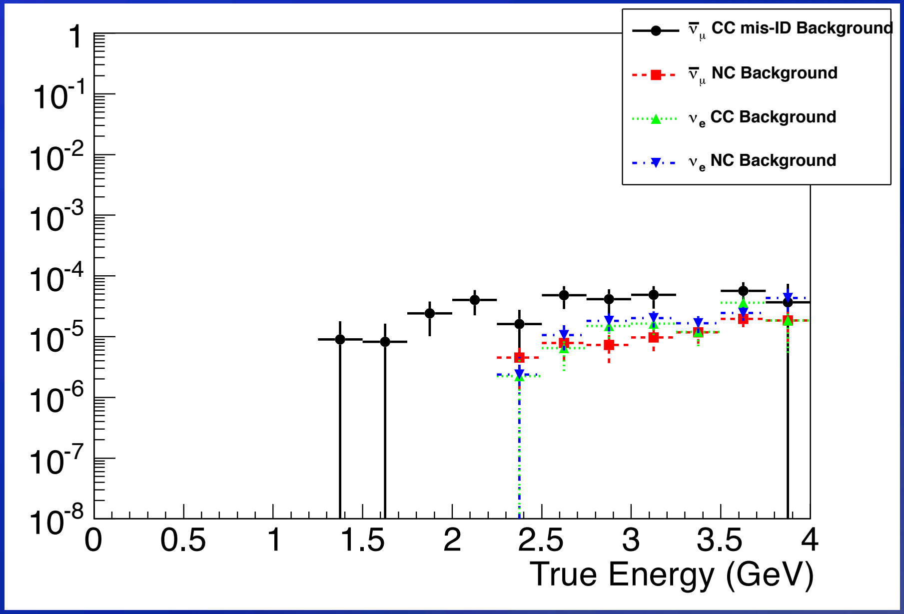
Ryan Bayes
Steve Bramsiepe
Glasgow

- Full GEANT4 Simulation
  - Extrapolation from ISS and IDS-NF studies for the MIND detector
  - Uses GENIE to generate the neutrino interactions.
  - Involves a flexible geometry that allows the dimensions of the detector to be altered easily (for optimization purposes, for example).
  - Have not used the detailed B field map, but parameterized fit is very good
  - Event selection/cuts
  - Multivariate analysis



Event reconstruction efficiency & Backgrounds



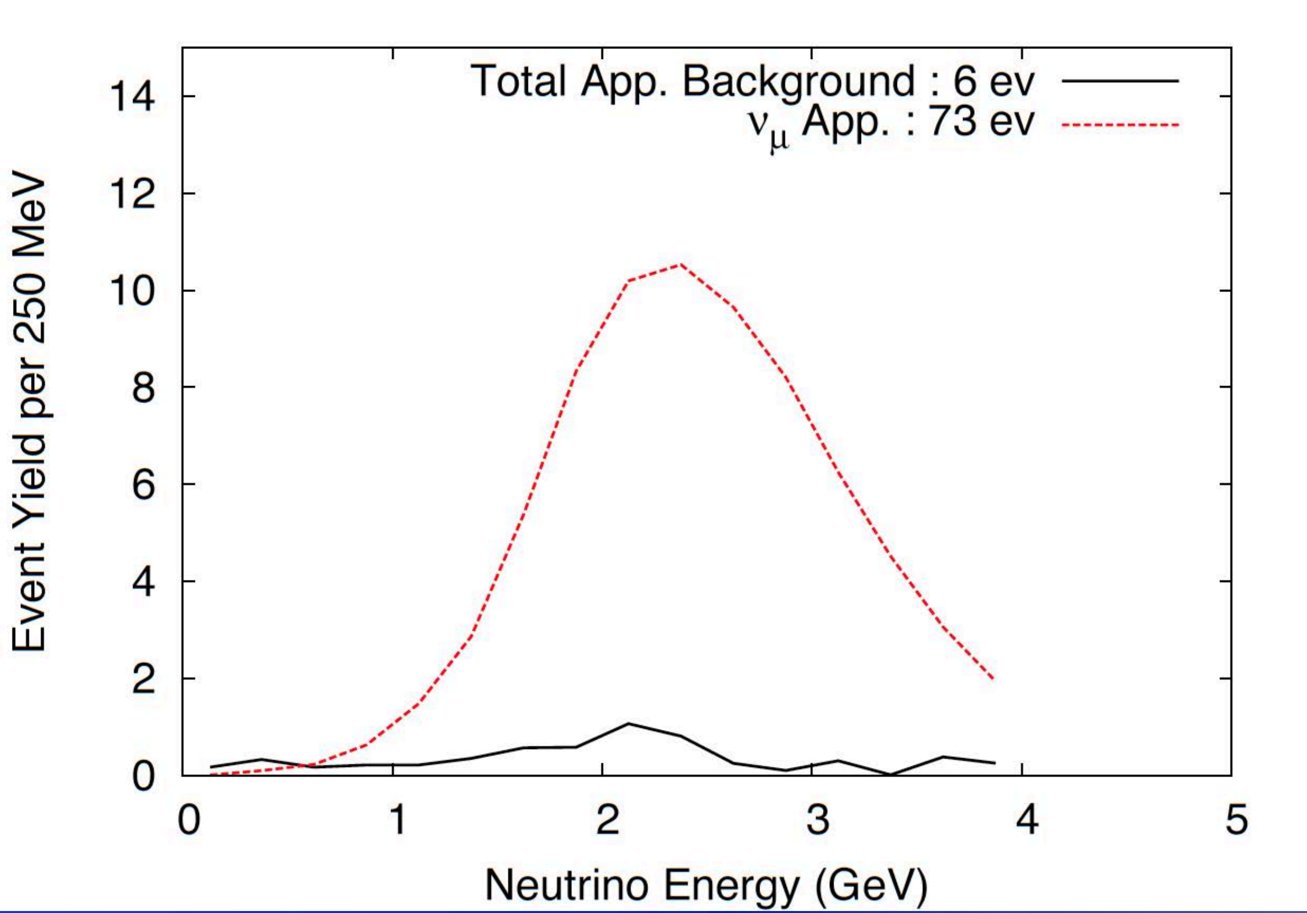


Signal efficiency

Background efficiency

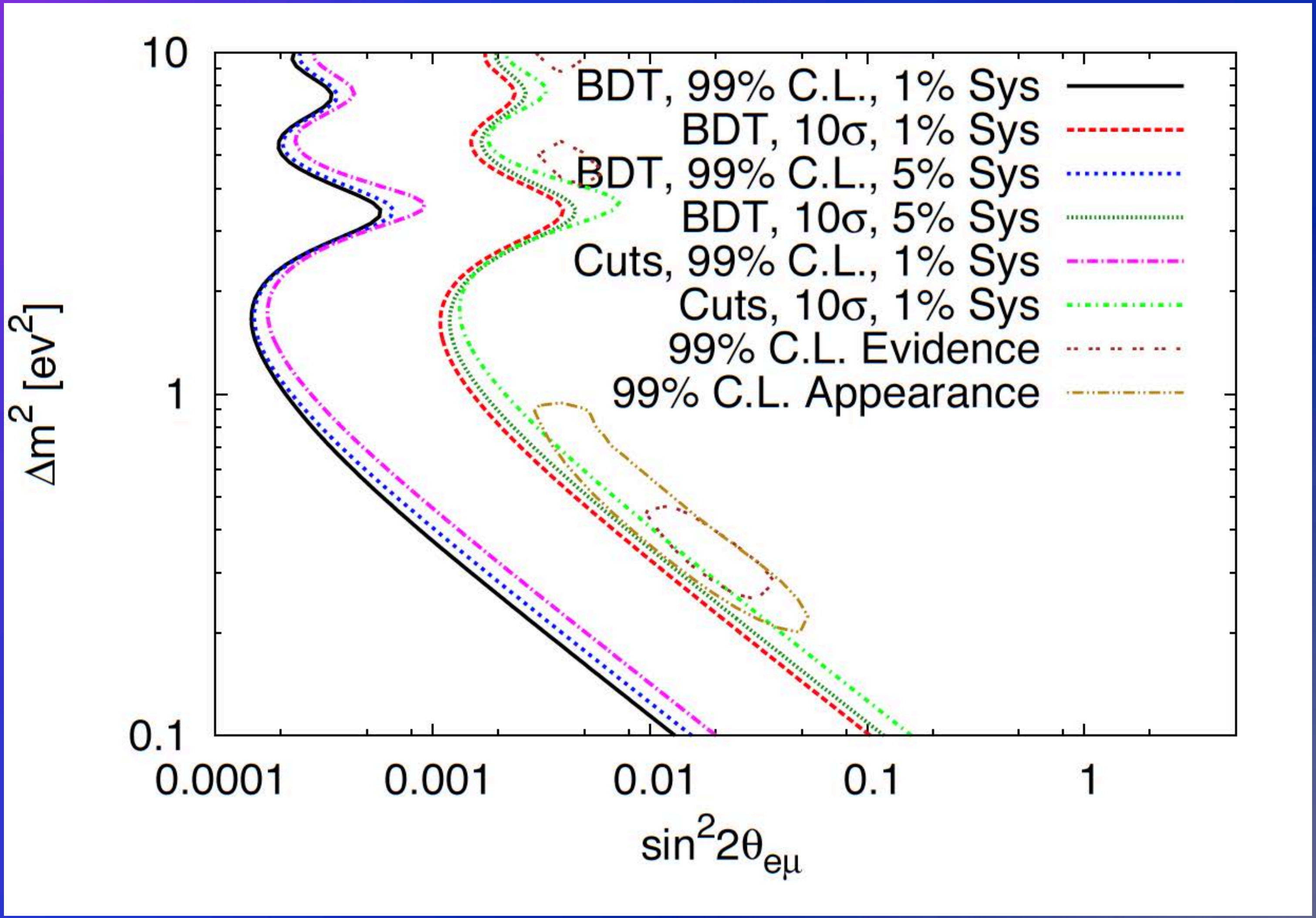
Boosted Decision Tree (BDT) analysis

$\nu_e \rightarrow \nu_\mu$ appearance
CPT invariant channel to MiniBooNE



S:B = 12:1

Appearance
Exclusion contours



Systematics for Golden Channel in nuSTORM

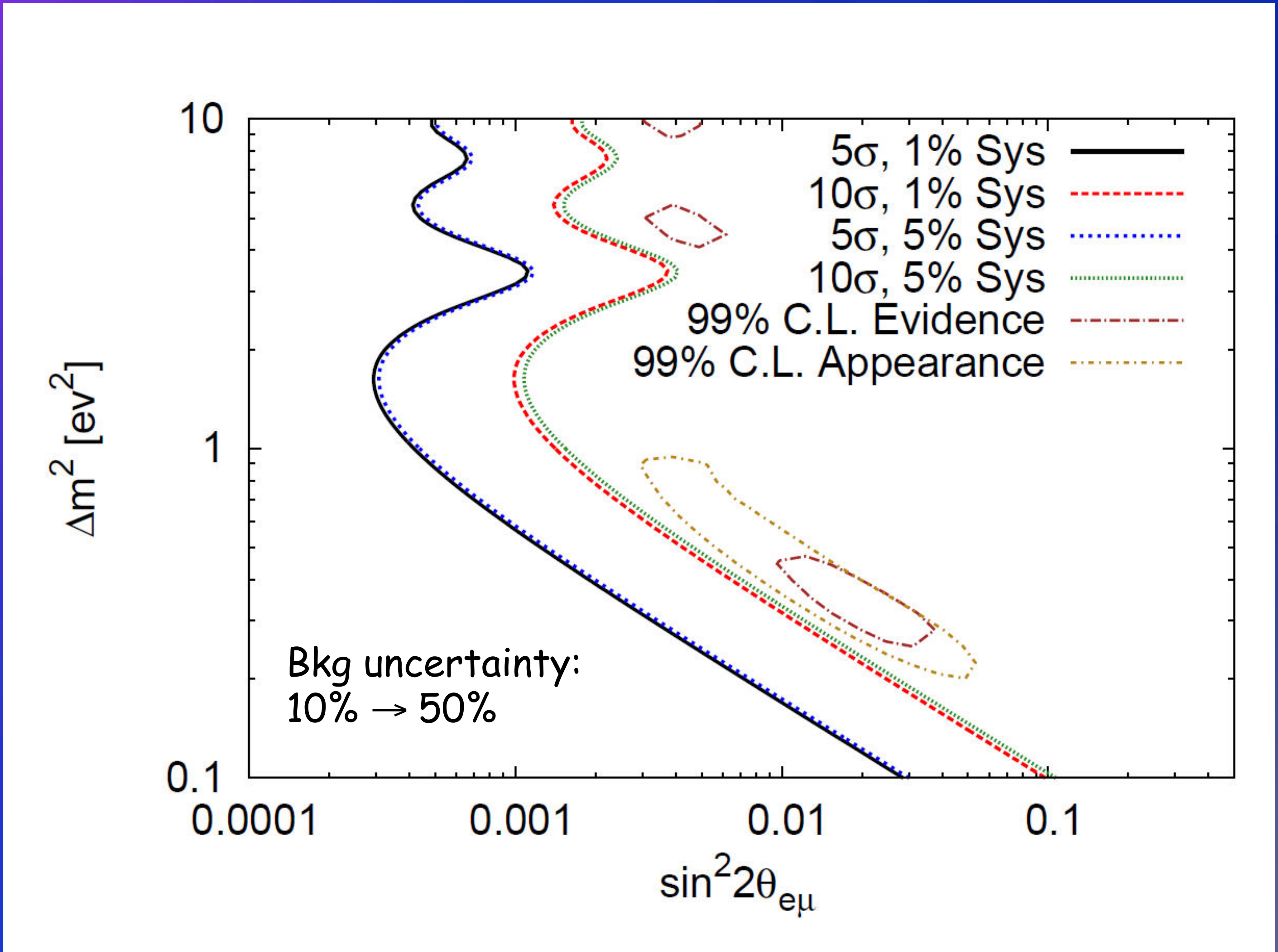
- Magnetic field uncertainties
  - If we do as well as MINOS (3%), no impact
  - Need high field, however. STL must work
- Cross sections and nuclear effects
  - Needs some more work
    - ND for disappearance ch (100T of SuperBIND) should minimize contribution to the uncertainties
- Cosmic rays
  - Not an issue (we do need to distinguish between upward and downward going muons via timing).
- Detector modeling (EM & Hadronic showering)
  - Experience from MINOS indicates we are OK, but this needs more work for SuperBIND
- Atmospheric neutrinos
  - Negligible
- Beam and rock muons
  - Active veto – no problem

Systematics II

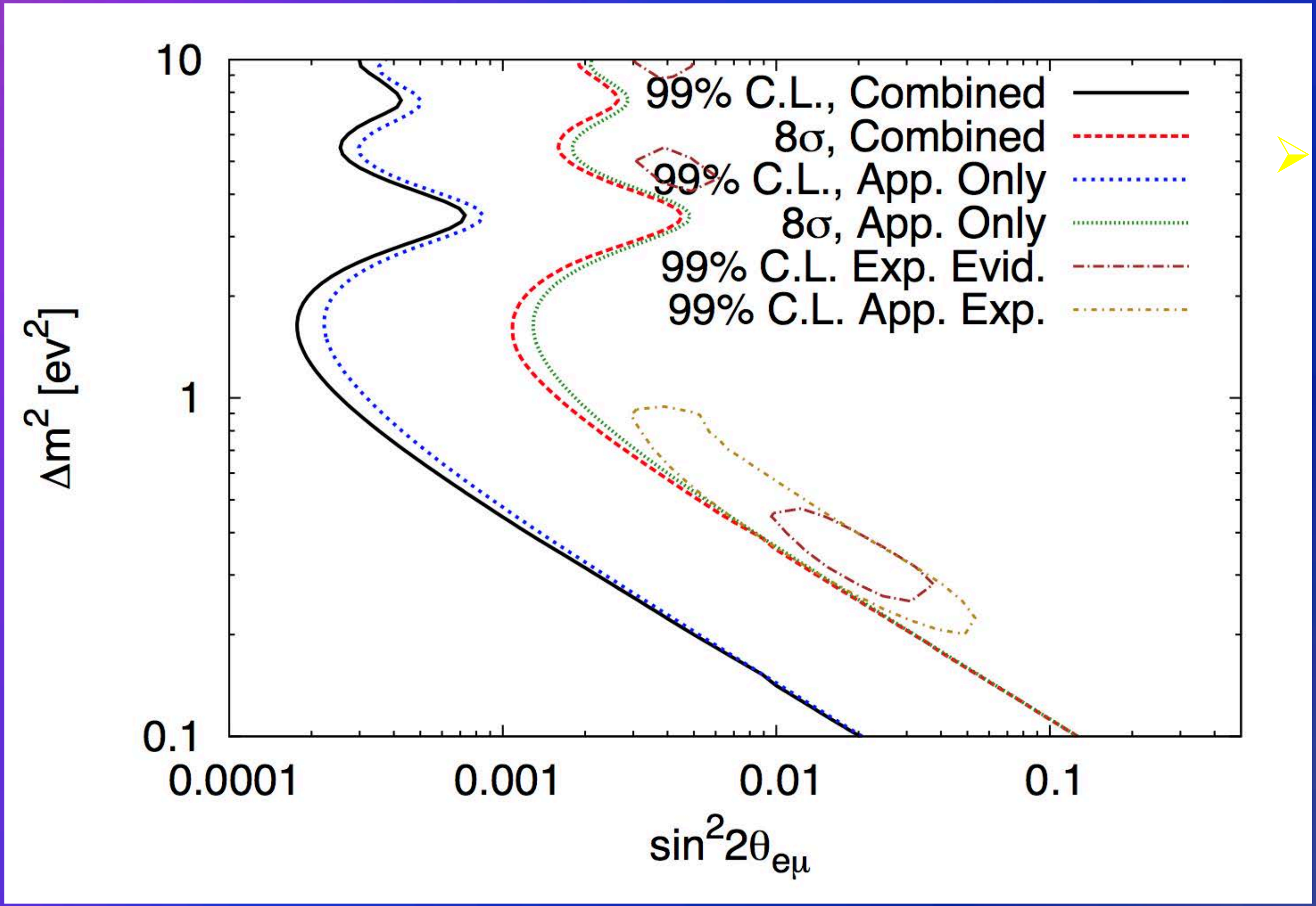
Uncertainty	Known Measures			Expected Contribution	
	Signal	Background	Reference	Signal	Background
Source luminosity	1%	1%	[229]	1%	1%
Cross section	4%	40%	[232]	0.5%	5%
Hadronic Model	0	15%	[233]	0	8%
Electromagnetic Model	2%	0	[233]	0.5%	0
Magnetic Field	<1%	<1%	[229]	<1%	<1%
Steel	0.2%	0.2%	[229]	0.2%	0.2%
Total	5%	43%		1%	10%

[232], [233] - MINOS

"Robustness" of appearance search



"Robustness" of appearance search II



- Approach to recover:
  - DR higher-order correction
    - $A_{dynamic}$ .6 -> .9 [1.5]
  - Target optimization
    - Medium-Z [1.5]

X2.25

Assuming 10^{20} POT/yr. for 5 years, 10σ contour becomes 8σ

Disappearance searches

Raw Event Rates

Neutrino mode with stored μ^+.

Channel	$N_{\text{osc.}}$	N_{null}	Diff.	$(N_{\text{osc.}} - N_{\text{null}})/\sqrt{N_{\text{null}}}$
$\nu_e \to \nu_\mu$ CC	332	0	∞	∞
$\bar{\nu}_\mu \to \bar{\nu}_\mu$ NC	47679	50073	-4.8%	-10.7
$\nu_e \to \nu_e$ NC	73941	78805	-6.2%	-17.3
$\bar{\nu}_\mu \to \bar{\nu}_\mu$ CC	122322	128433	-4.8%	-17.1
$\nu_e \to \nu_e$ CC	216657	230766	-6.1%	-29.4

Anti-neutrino mode with stored μ^-.

Channel	$N_{\text{osc.}}$	N_{null}	Diff.	$(N_{\text{osc.}} - N_{\text{null}})/\sqrt{N_{\text{null}}}$
$\bar{\nu}_e \to \bar{\nu}_\mu$ CC	117	0	∞	∞
$\bar{\nu}_e \to \bar{\nu}_e$ NC	30511	32481	-6.1%	-10.9
$\nu_\mu \to \nu_\mu$ NC	66037	69420	-4.9%	-12.8
$\bar{\nu}_e \to \bar{\nu}_e$ CC	77600	82589	-6.0%	-17.4
$\nu_\mu \to \nu_\mu$ CC	197284	207274	-4.8%	-21.9

μ dis. channels follow naturally from μ appear.

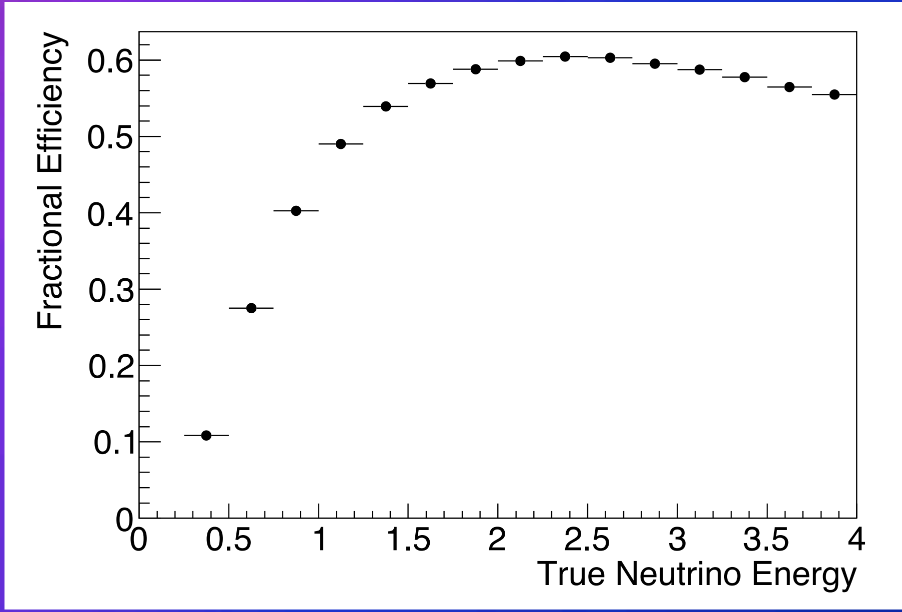
ν_e channels will take more work

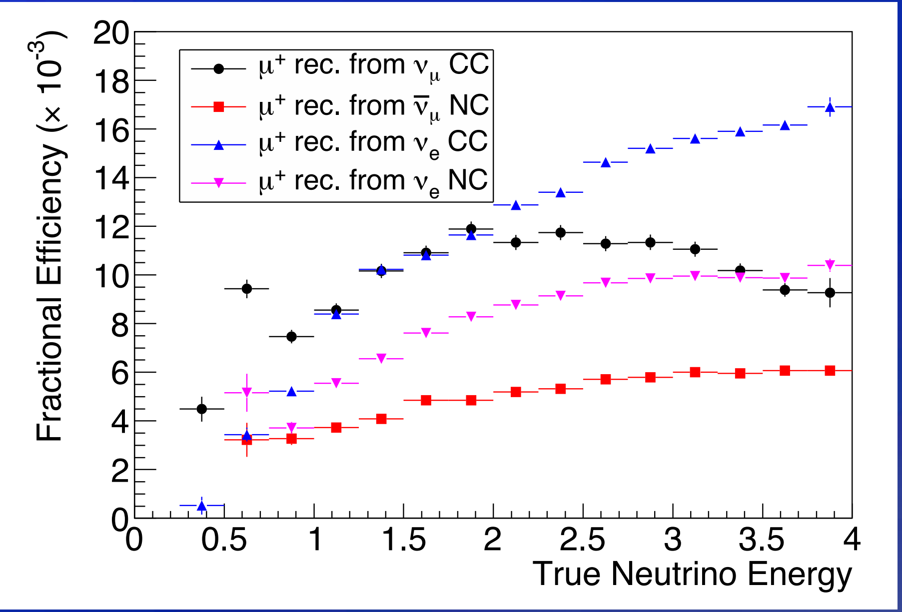
Tremendous Statistical Significance

3+1 Assumption

Appearance channels

ν_μ disappearance analysis

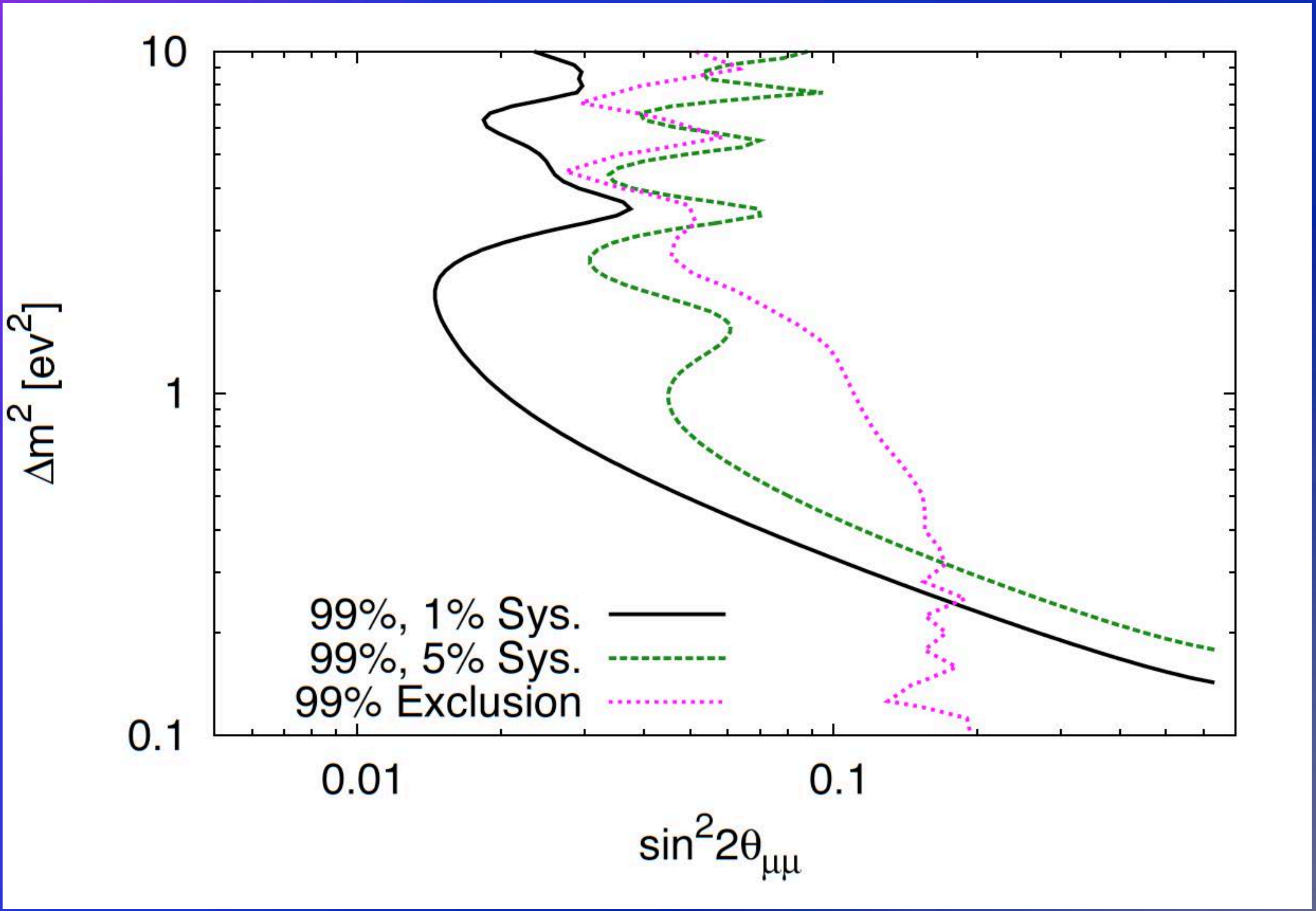




Efficiency

Background

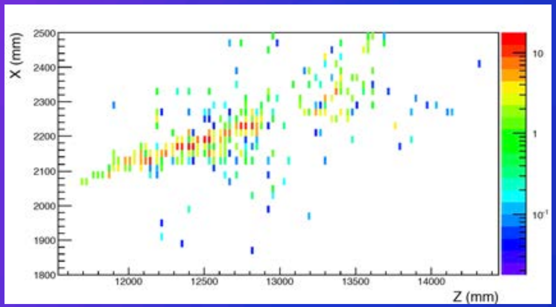
ν_μ disappearance



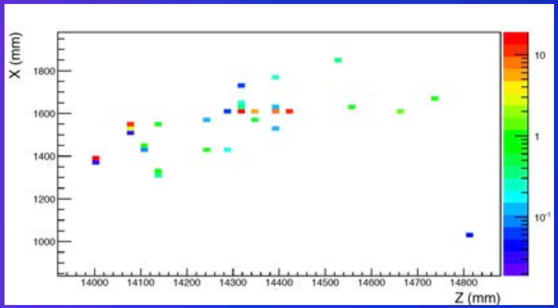
Preliminary ν_e work

David Adey
Fermilab

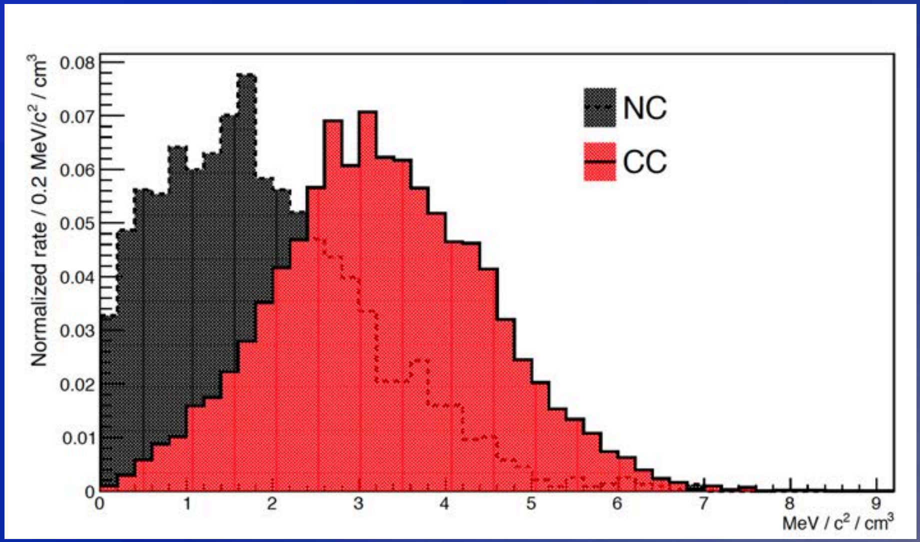
- SuperBIND is not the ideal detector for ν_e interaction physics or for the study of NC.
- However, SuperBIND's aggressive design does provide opportunity to study ν_e disappearance.
  - CC-NC distinction required for these types of events could also provide an option to study NC disappearance.



ν_e CC



NC



Cuts-based analysis lacks discrimination power. MVA approach needed

Disappearance channels

Walter Winter
Würzburg

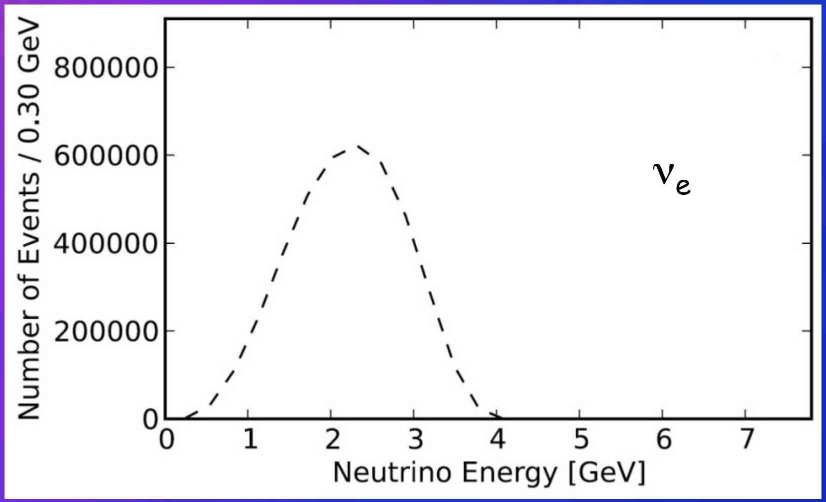
But:

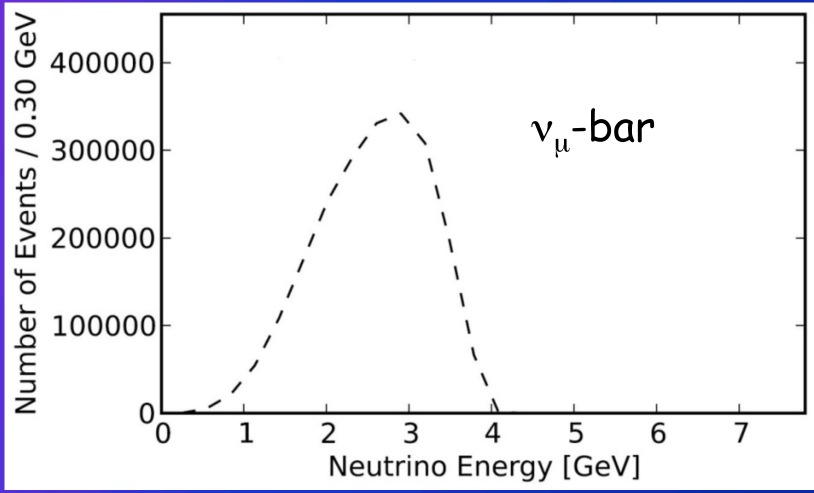
- Need self-consistent two-detector simulation including (bin-to-bin) uncorrelated shape error ~ 10%
- A challenge: there may be oscillations already in near detectors
  - Geometry important for $\Delta m^2 \sim 10^1 - 10^3\ \mathrm{eV}^2$
- Suitability (& optimization) of SuperBIND for ν_e channels still needs to be studied

ν Interaction Physics

Preliminary studies

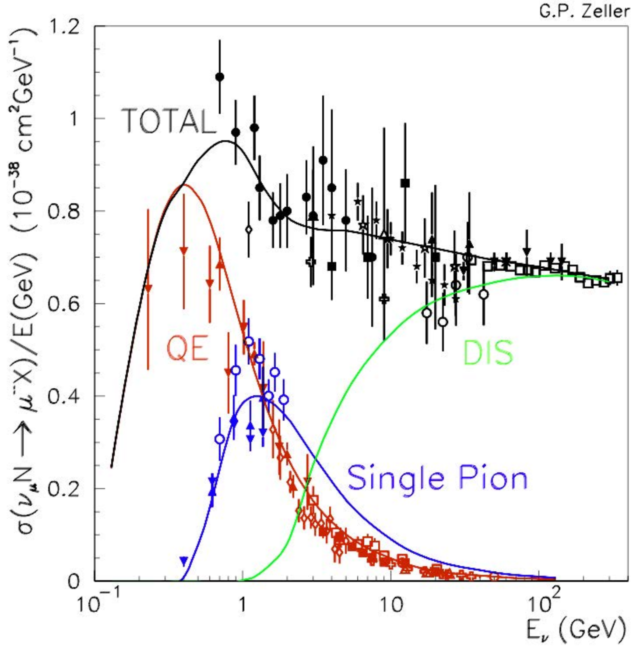
E_ν spectra (μ^+ stored)





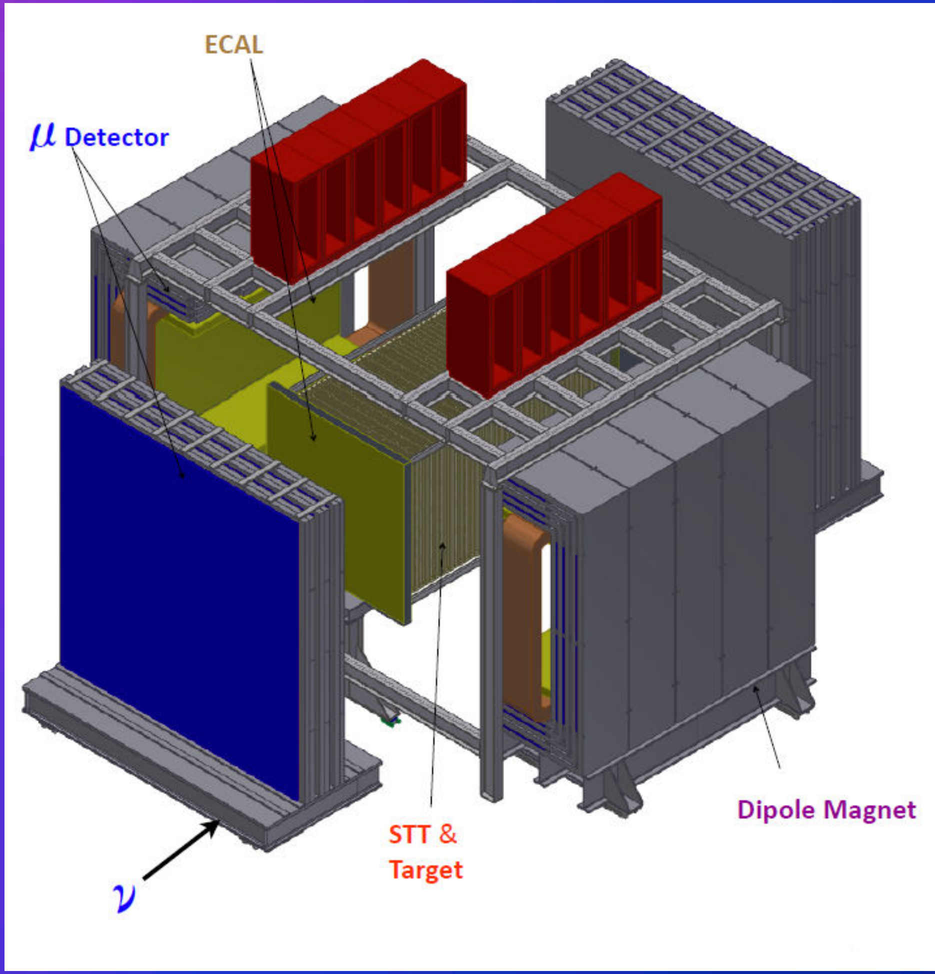
Event rates/100T at ND hall 50m from straight with μ^+ stored

Channel	N_{evts}
$\bar{\nu}_\mu$ NC	844,793
ν_e NC	1,387,698
$\bar{\nu}_\mu$ CC	2,145,632
ν_e CC	3,960,421



A detector for ν interaction physics
One Example

Sanjib Mishra

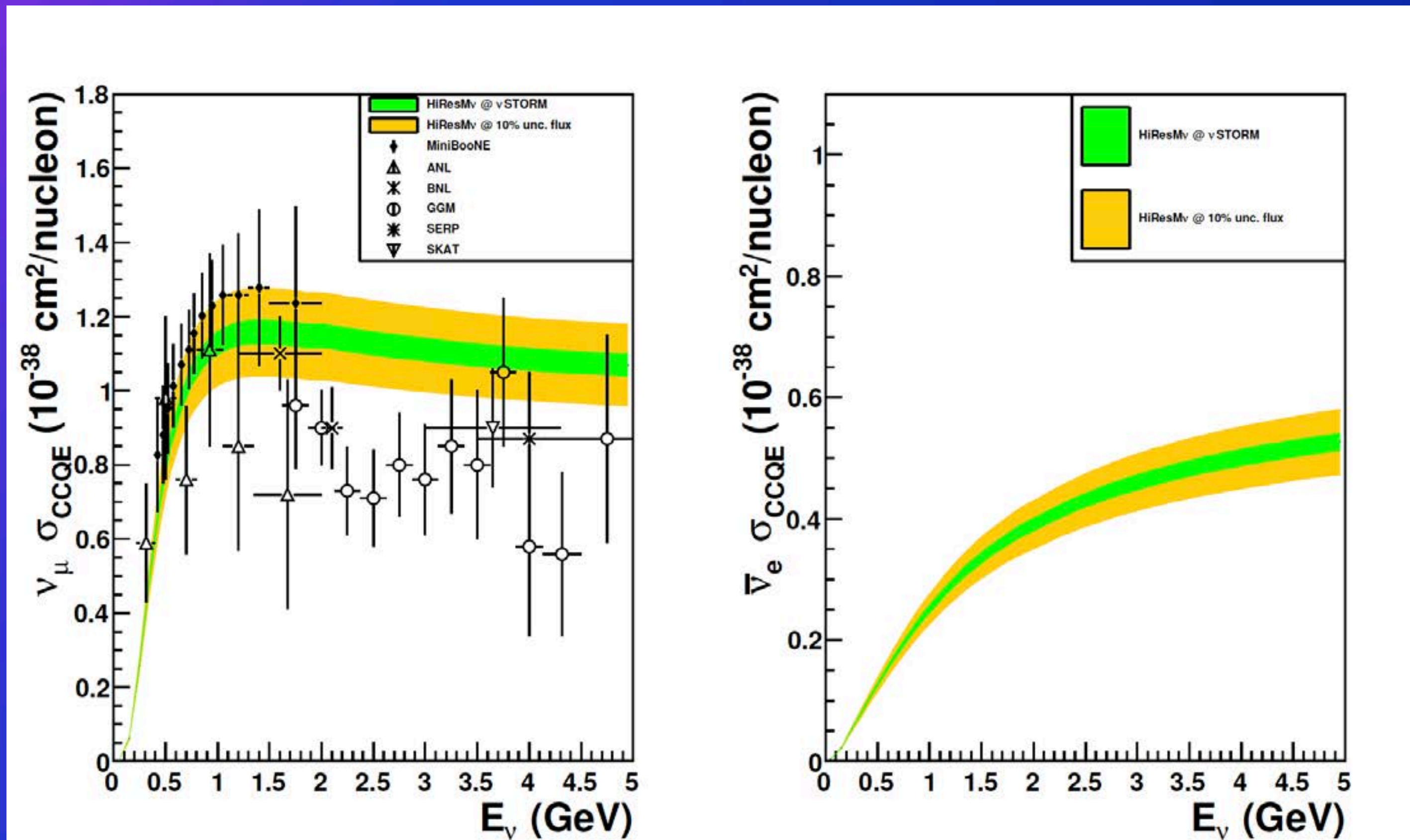


- HiResMν
  - Evolution of the NOMAD experiment
  - One of the concepts considered for ND for LBNE
  - Studied as ND for NF
- Capabilities
  - High resolution spectrometer
  - Low density
  - PID & tracking
  - Nuclear targets

Cross section measurements

Edward Santos
Imperial

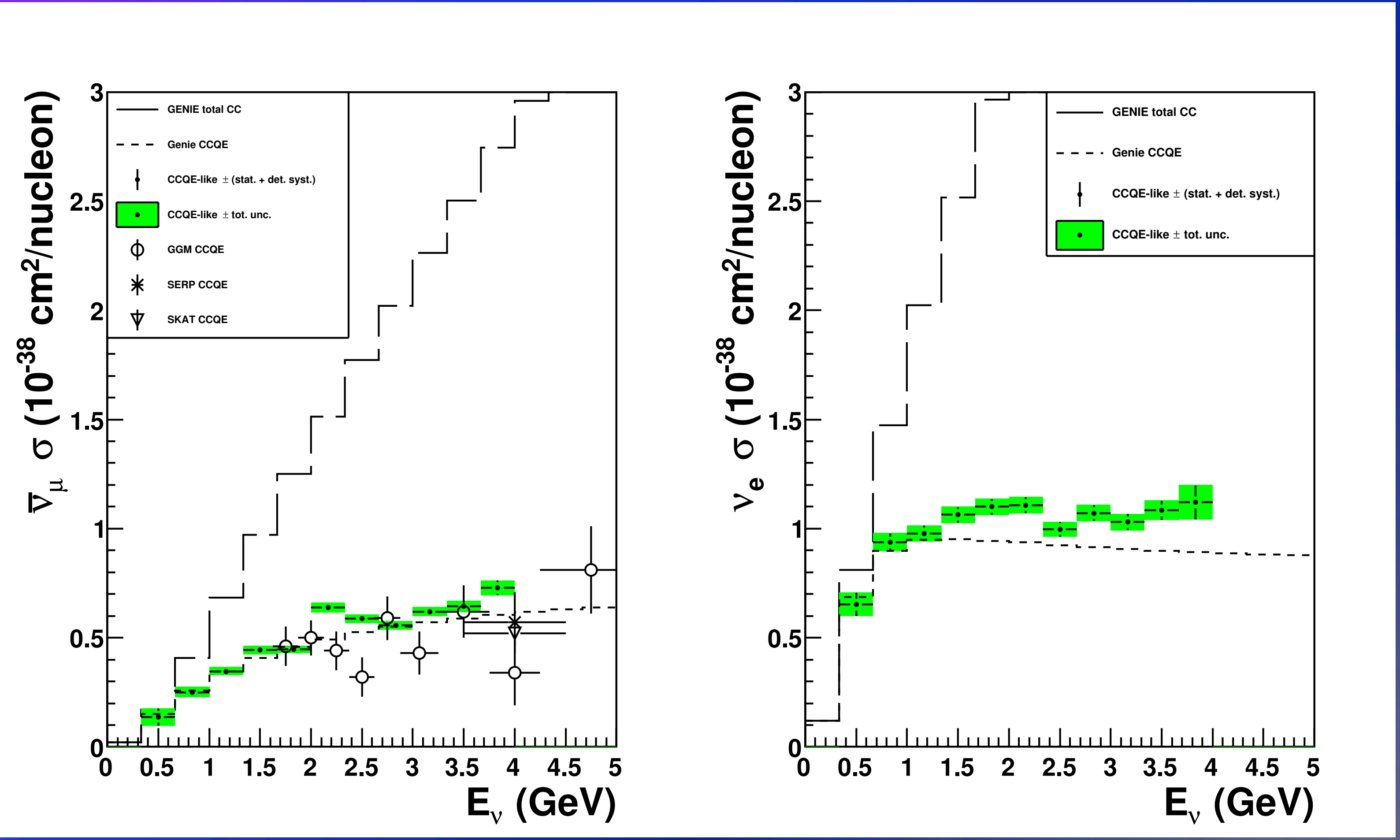
μ^+



μ^-

HIRESMν – systematics only

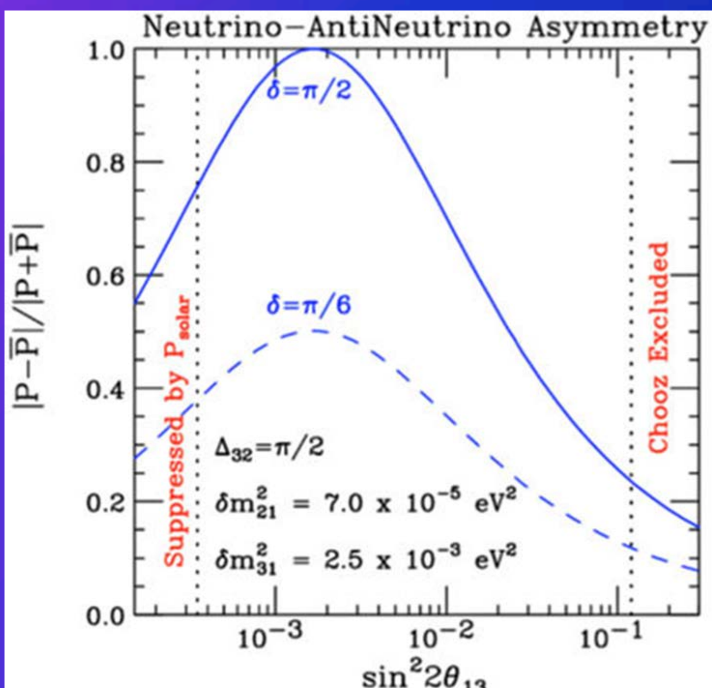
Straw man Detector
μBooNE



ν Cross-section measurements

Cross-section measurements

- μ storage ring presents only way to measure ν_μ & ν_e & (ν and $\bar{\nu}$) x-sections in same experiment
  - Supports future long-baseline experiments



$$\frac{P(\nu_\mu \rightarrow \nu_e) - P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)}{P(\nu_\mu \rightarrow \nu_e) + P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)}$$

- Important to note that with θ_{13} large, the asymmetry you're trying to measure is small, so:
  - Bkg content & uncertainties start to become more important
  - A "better" understanding of ν/vbar cross-sections beneficial

Accelerator R&D

Looking Forward

Looking Forward: Beyond ν physics

Friends in High Places

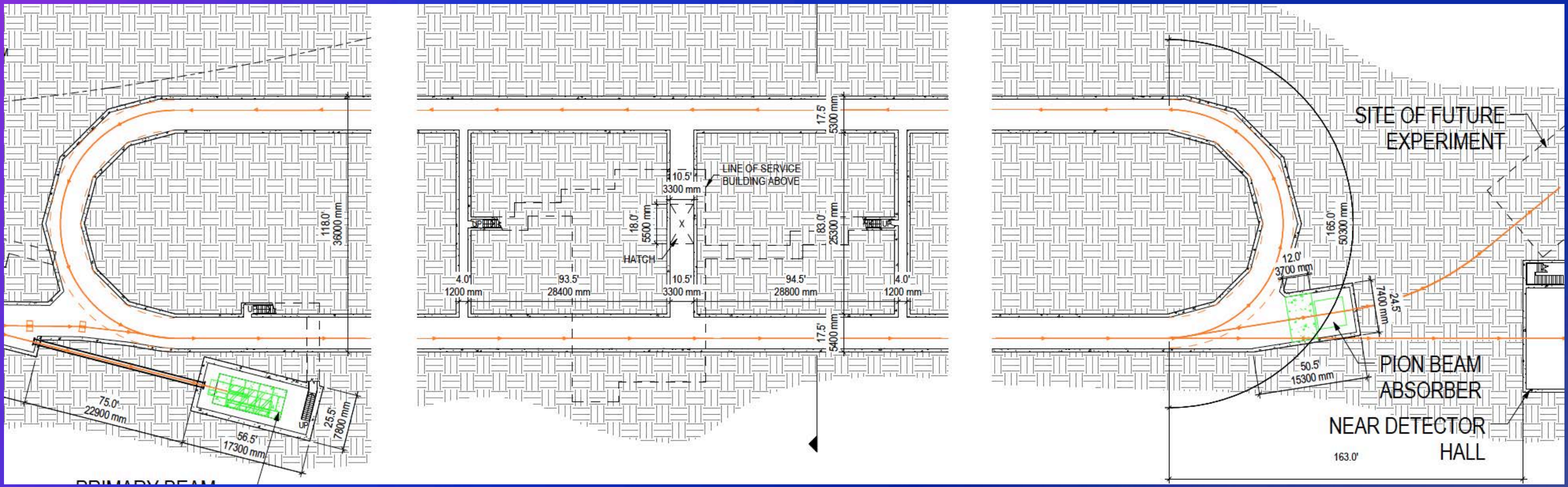
Conclusions (cont)

- The recent discovery of the Higgs particle of 125 GeV at CERN has brought in also the additional requirement of a remarkably small longitudinal emittance.
- The unique feature of the direct production of a H° scalar in the s-state is that the mass, total width and all partial widths of the H° can be directly measured with remarkable accuracy.
- The main innovative component could be the practical and experimental realization of a *full scale cooling demonstrator*, a relatively modest and low cost system but capable to conclusively demonstrate "ionization cooling" at the level required for a Higgs factory and eventually as premise for a subsequent multi-TeV collider and/or a long distance ν factory
- The additional but conventional facilities necessary to realize the facility with the appropriate luminosity should be constructed *only after the success of this "initial cooling experiment" has been conclusively demonstrated*.

Venice_March2013 Slide# : 38

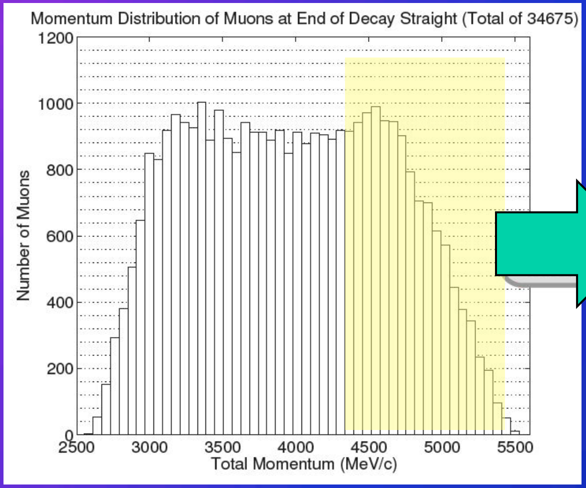
C. Rubbia, Neutrino Telescopes 2013

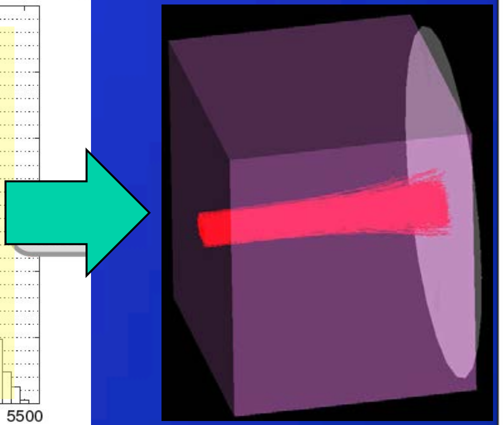
nuSTORM
Setting the stage for the next step

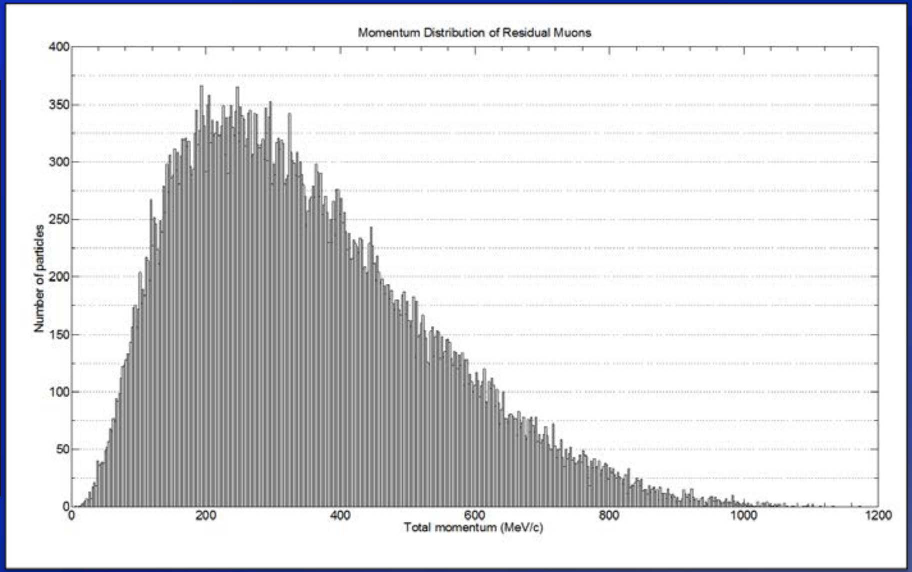


Only ~50% of πs decay in straight
Need π absorber

Low Energy μ beam



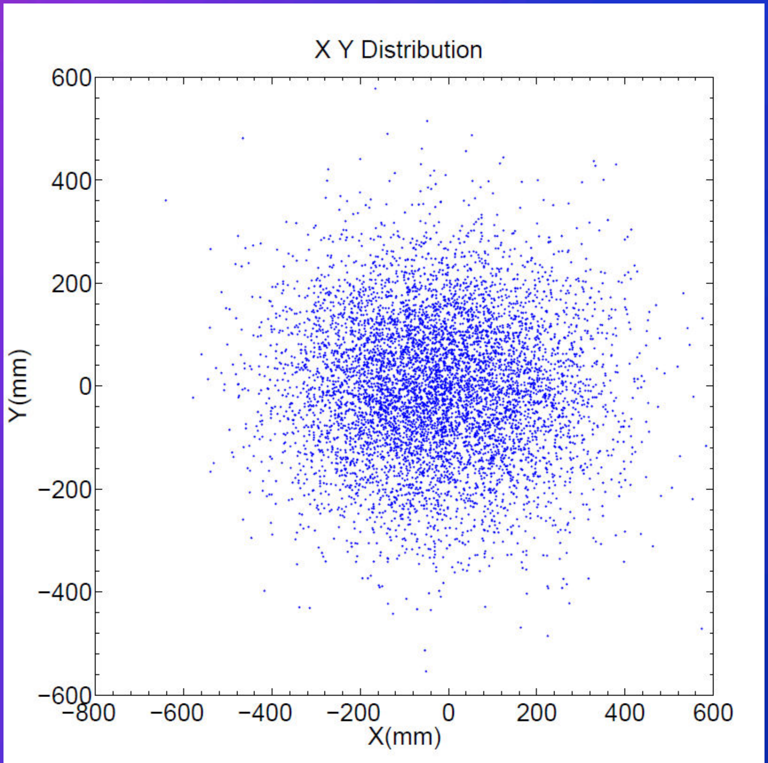


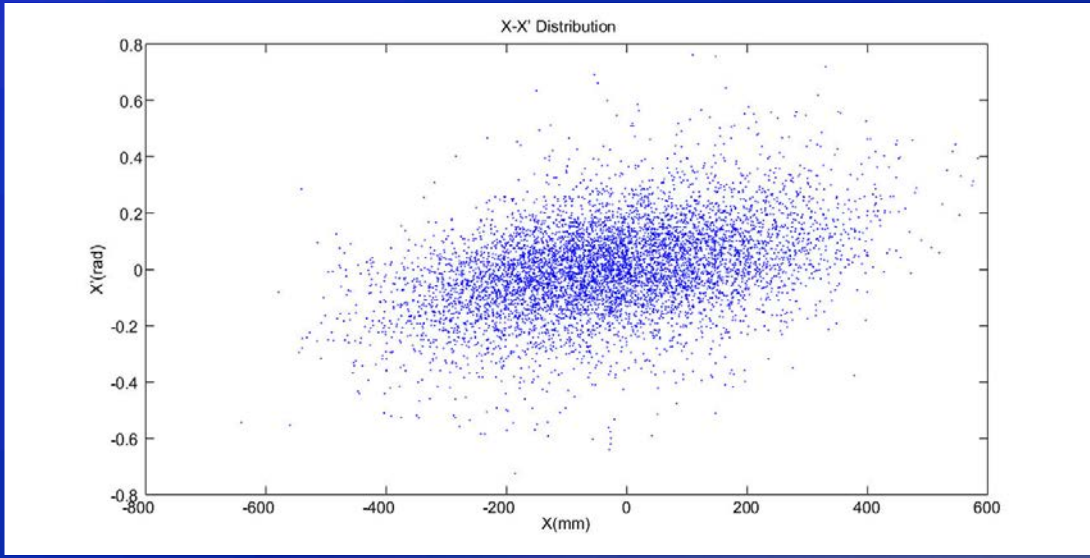


At end of straight we have a lot of πs, but also a lot of μs with $4.5 < P(\mathrm{GeV/c}) < 5.5$

After 3.48m Fe, we have $\approx 10^{10}$ μ/pulse in $100 < P(\mathrm{MeV/c}) < 300$

Input beam for some future 6D μ cooling experiment(s)





Project Definition Report

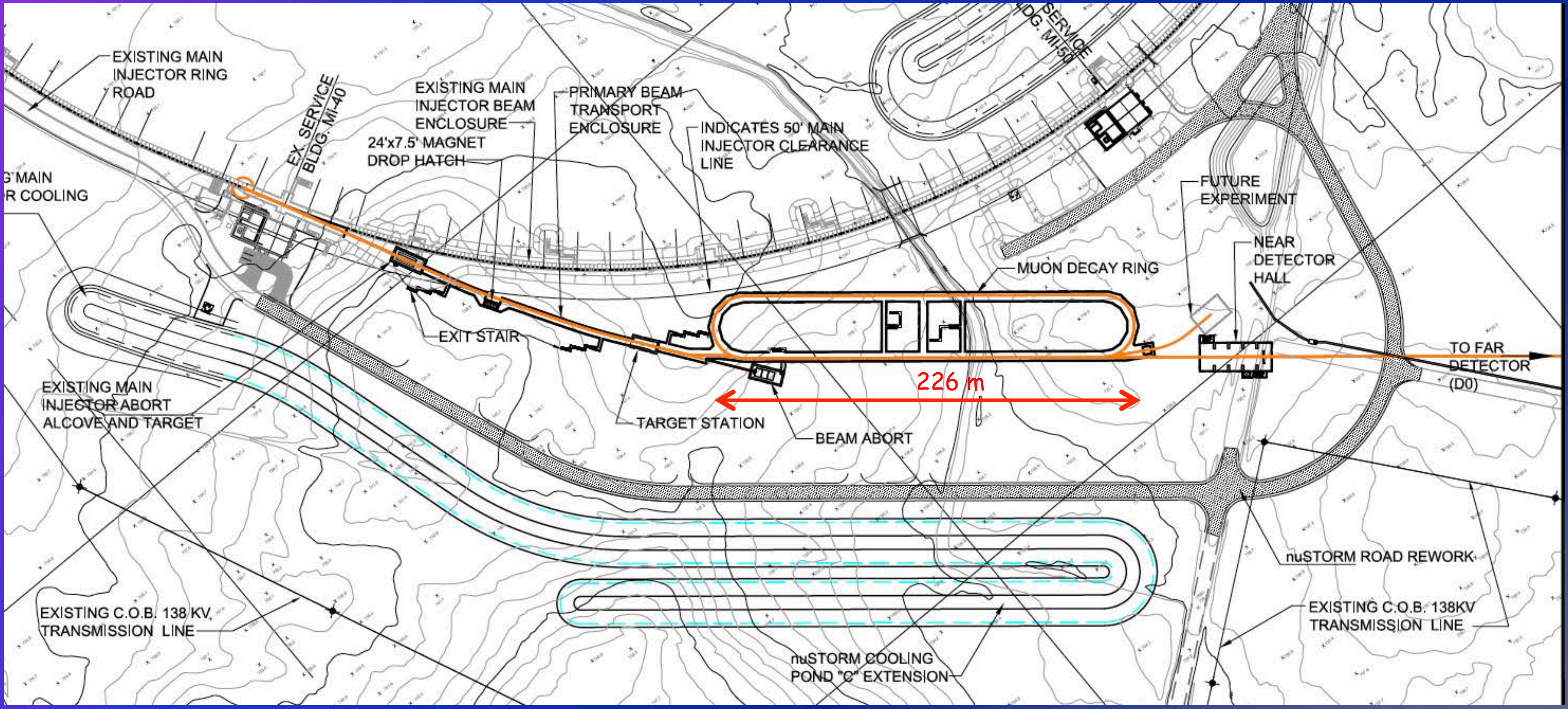
Fermilab

νSTORM

Siting Plan

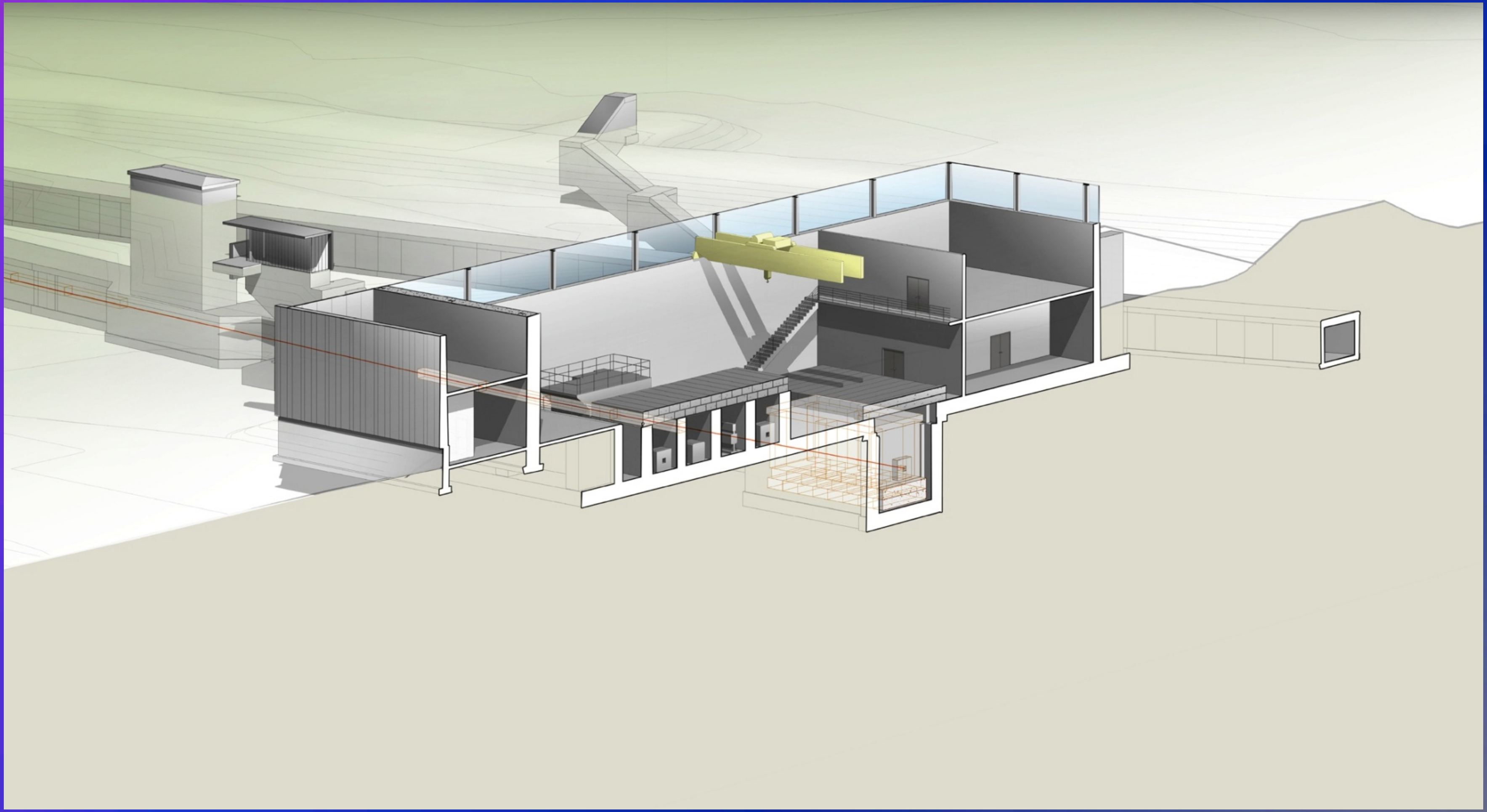
Steve Dixon
Fermilab FESS

Site schematic

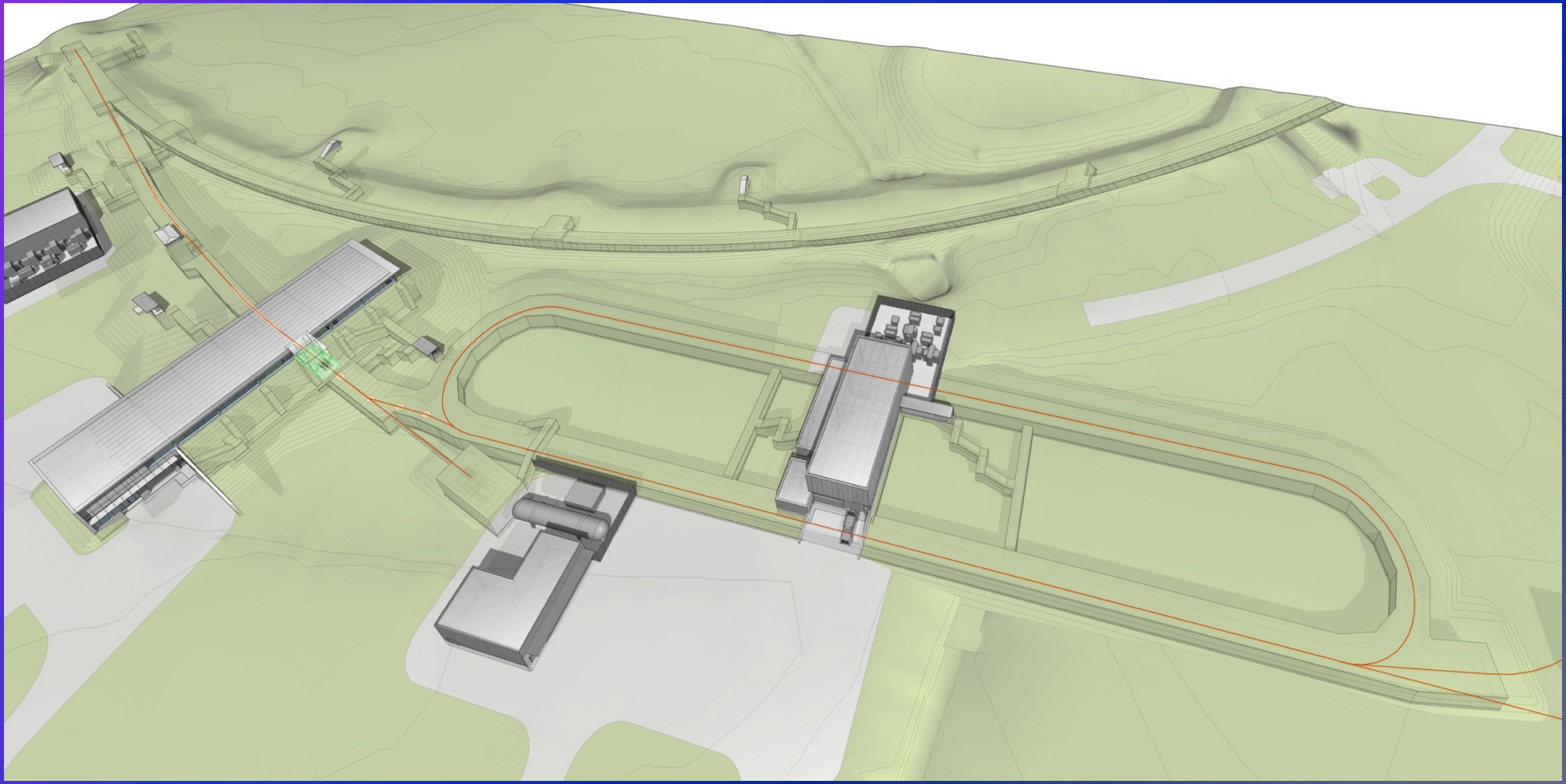


Target Station

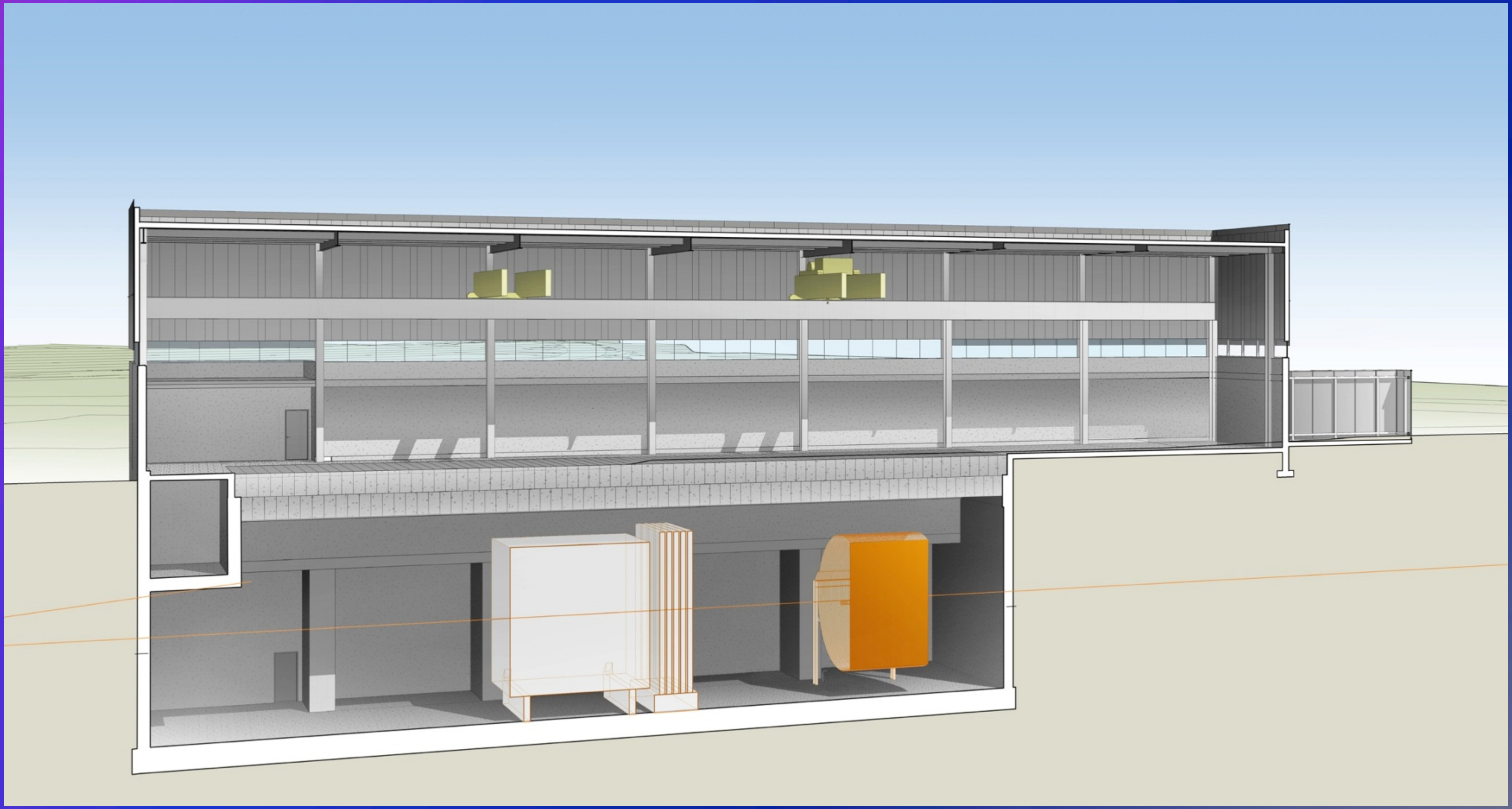
TS section



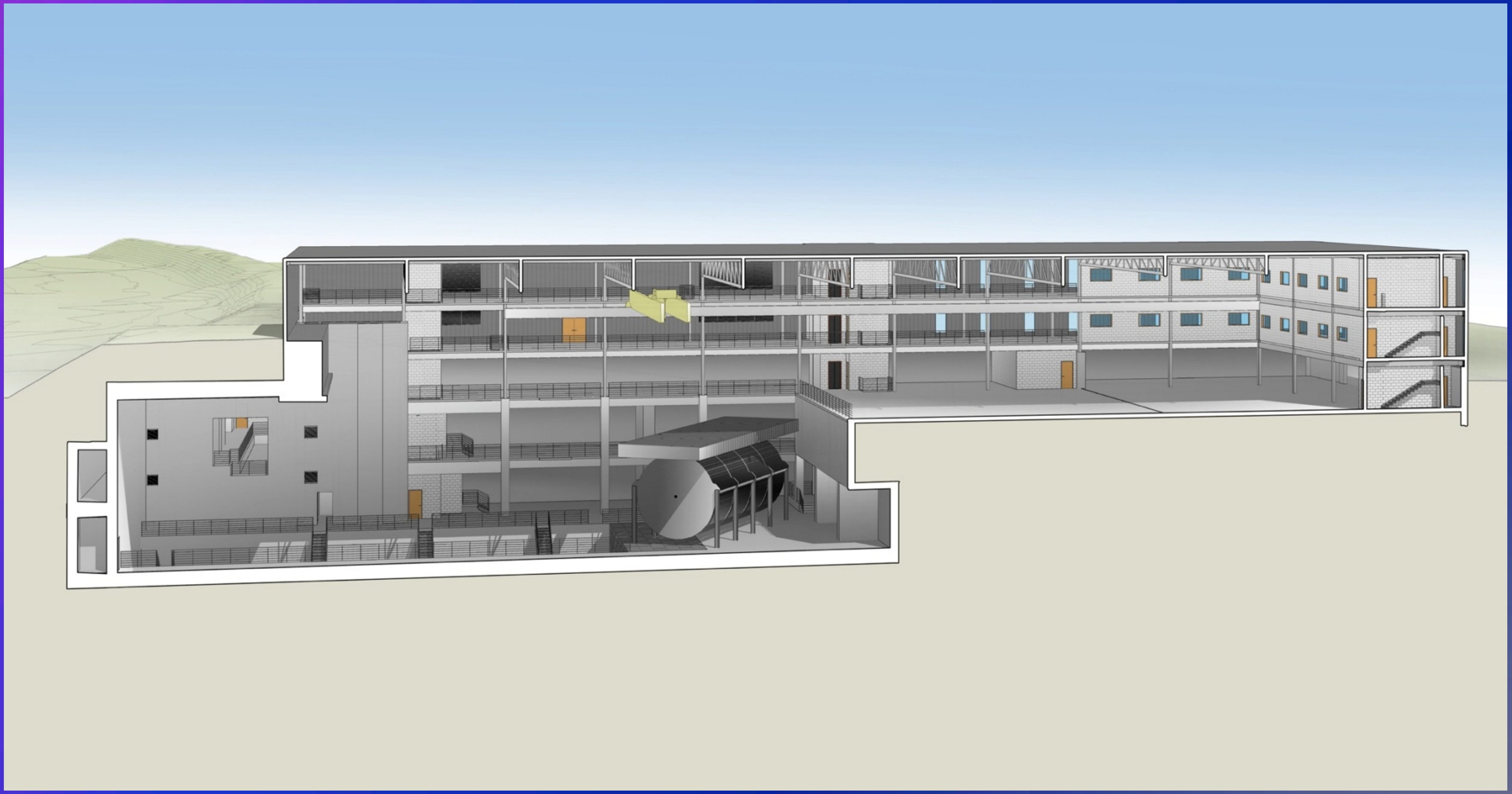
Decay ring



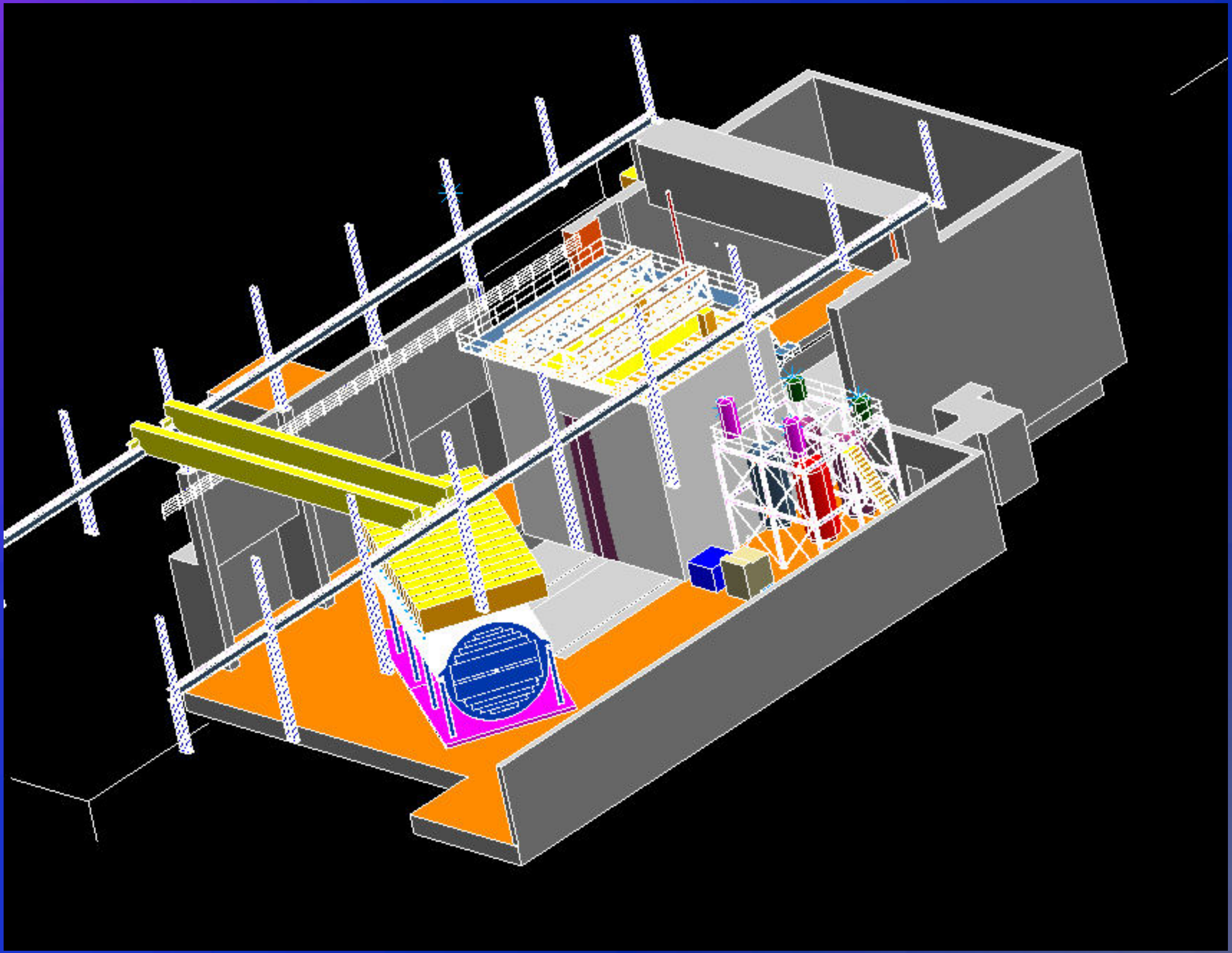
Near detector hall



Far Detector Hall
D0 Assembly Building



nuSTORM Far Detector Hall



Costing

Costing model

Basis of Estimation

- Conventional facilities
  - PDR
- Cost estimates from AD for
  - Primary beam line
  - Target Station
- Cross-checks to LBNE
- Magnet Costs based on construction analysis for room temperature magnets and on Strauss & Green model for SC magnets (TD)

nuSTORM Costing

Sub System	Cost M$
Primary Beam Line	28.5
Target Station	37.9
Transport Line	16.5
Decay Ring	135.2
Near Hall	23.5[1]
SuperBIND	27.1[2]
Site work	27
Other	2.5
Sub Total	**298.2**
Management	37.1[3]
Total	**335.3**

Total contingency – 45%

[1]Near Hall sized for multiple experiments & ND for SBL oscillation physics
[2]1.3kT Far + .2kT Near & include DAB work
[3]Assumes LBNE estimates: Proj. Office (10%), L2 (9.4%), L3 (4%)

nuSTORM Costing
Comparison to Jan '13 estimate

Sub System	Cost M$	
Primary Beam Line	24	28.5
Target Station	56	37.9
Transport Line	14	16.5
Decay Ring	82	135.2
Near Hall	29	23.5
Far Detector	24	27.1
Site work	--	27
Other	--	2.5
Sub Total	**229**	**298.2**
Management	34	37.1
Total	**263**	**335.3**

Moving Forward

Important steps to move forward

- Stage I approval from this committee would be nice
- Presentation to the CERN SPSC on June 25th
  - First formal presentation regarding nuSTORM at CERN
    - Our collaboration submitted EOI in April
- Continue our nuSTORM workshops
  - Next at Fermilab with emphasis on ν interaction physics
- Technical
  - Decay ring optimization
    - Recover compact (350 m) “design”?
    - Explore lattice with no SC magnets
  - Target
    - Medium-Z target (Inconel/Invar)?

Request

Table 32: Support request

Task	Division	Effort type	FTE
π production simulations	APC	S	0.15
Inconel target studies	AD	E	1.0
Proton beamline optimization	AD	S/E	0.3
Decay ring lattice studies	AD	S	0.3
Kicker design	AD	E	0.2
Magnet design	TD	S/E/D	1.0
Decay ring instrumentation design	AD	E	0.5

S:Scientist, E: Engineer, D:Designer/draftsman

nuSTORM EOI to CERN

- Twin-Track Approach
  - Develop International support at the Laboratory level for the concept
    - Bottom-up (grass roots) & Top-down
- Has produced significant increase in the size of the collaboration
  - From 38 at time of Fermilab LOI to 110 now (single collaboration)
- CERN EOI has requested support to:
  - Investigate in detail how nuSTORM could be implemented at CERN; and
  - Develop options for decisive European contributions to the nuSTORM facility and experimental program wherever the facility is sited.
- It defines a roughly two-year program which culminates in the delivery of a Technical Design Report.
- Submitted in April of this year.
- Will be presented to the SPSC at its June 25th meeting.

nuSTORM: Conclusions

The Physics case:

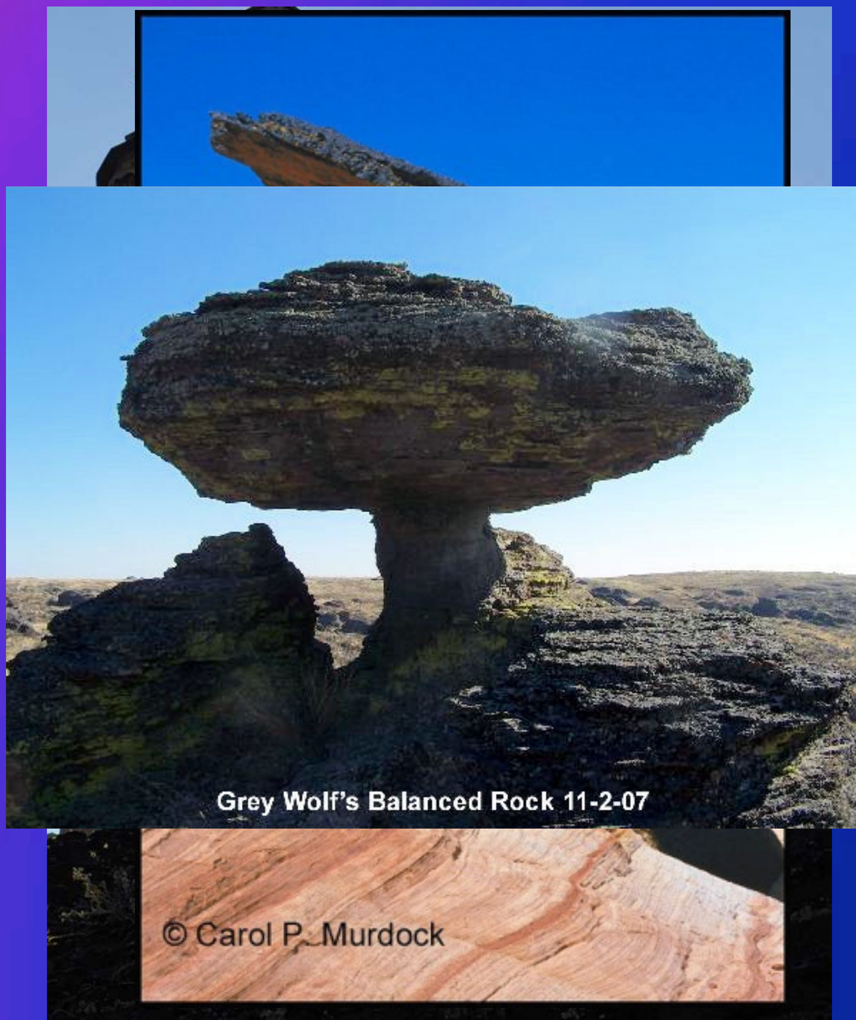
- Simulation work indicates we can confirm/exclude at 10σ (CPT invariant channel) the LSND/MiniBooNE result
  - ν_μ and (ν_e) disappearance experiments delivering at the <1% level look to be doable
    - Systematics need careful analysis
    - Detailed simulation work on these channels has not yet started
- ν interaction physics studies with near detector(s) offer a unique opportunity & can be extended to cover 0.2<GeV< E_ν< 4 GeV
  - Could be *"transformational"* w/r to ν interaction physics
  - For this physics, nuSTORM should really be thought of as a facility: A ν *"light-source"* is a good analogy
    - nuSTORM provides the beam & users will bring their detector to the near hall

Conclusions II

The Facility:

- Presents very manageable extrapolations from existing technology
  - But can explore new ideas regarding beam optics and instrumentation
- Offers opportunities for extensions
  - Add RF for bunching/acceleration/phase space manipulation
    - Provide μ source for 6D cooling experiment with intense pulsed beam
- Utilizes existing Fermilab infrastructure very effectively

Three Pillars of nuSTORM



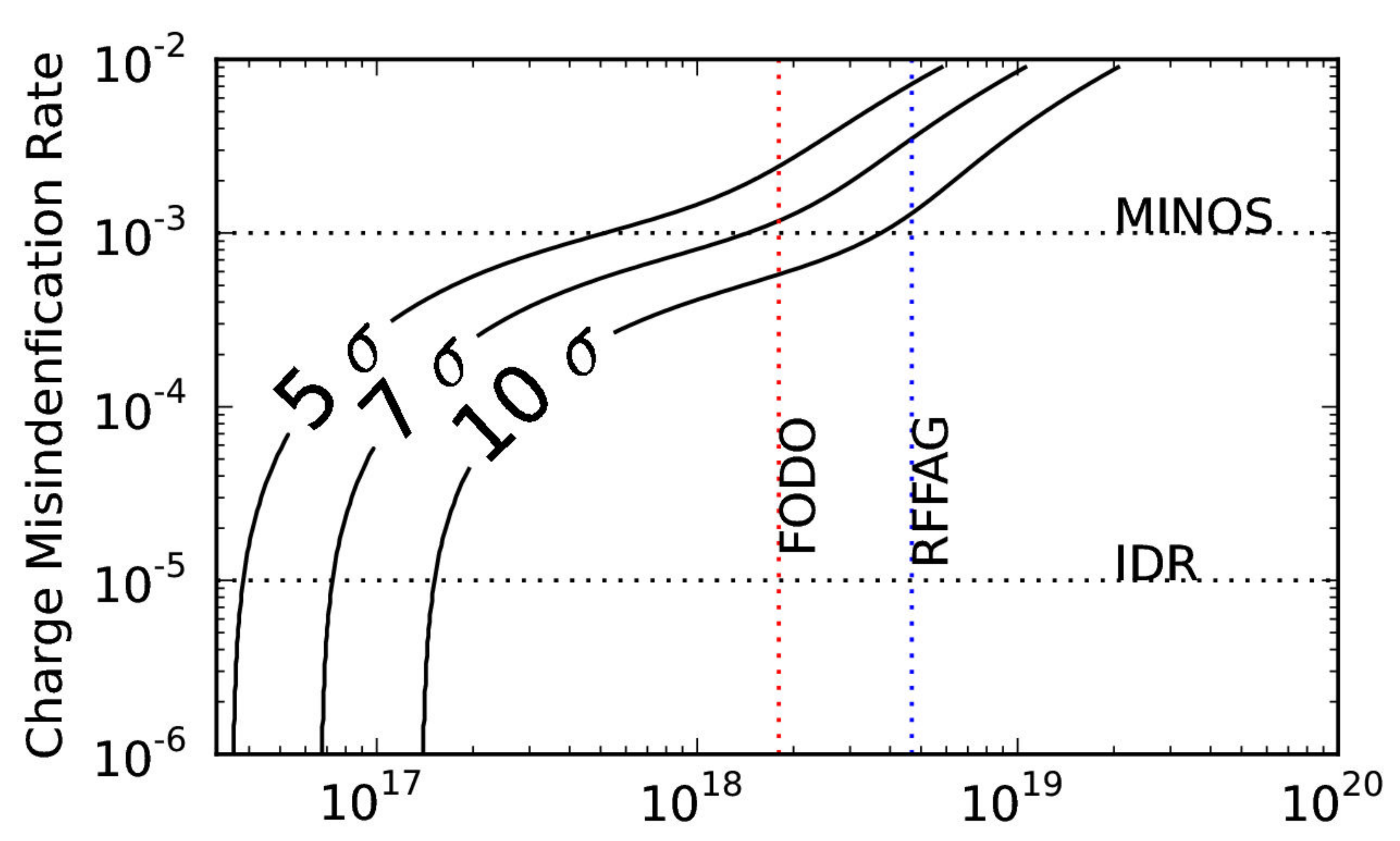
- Deli... rs o... the physics fo... of sterile ν
  - O... a new approach to th... tion of ν beams ... σ benchmark to make ...finitive statement w/r LSND/ MiniBooNE
- Can add significantly to our knowledge of ν interactions, particularly for ν_e
  - ν *"Light Source"*
- Provide... accelerator & detect... echnology test bed

Thank you

Back Ups

Required μ charge mis-ID rate needed for given sensitivity

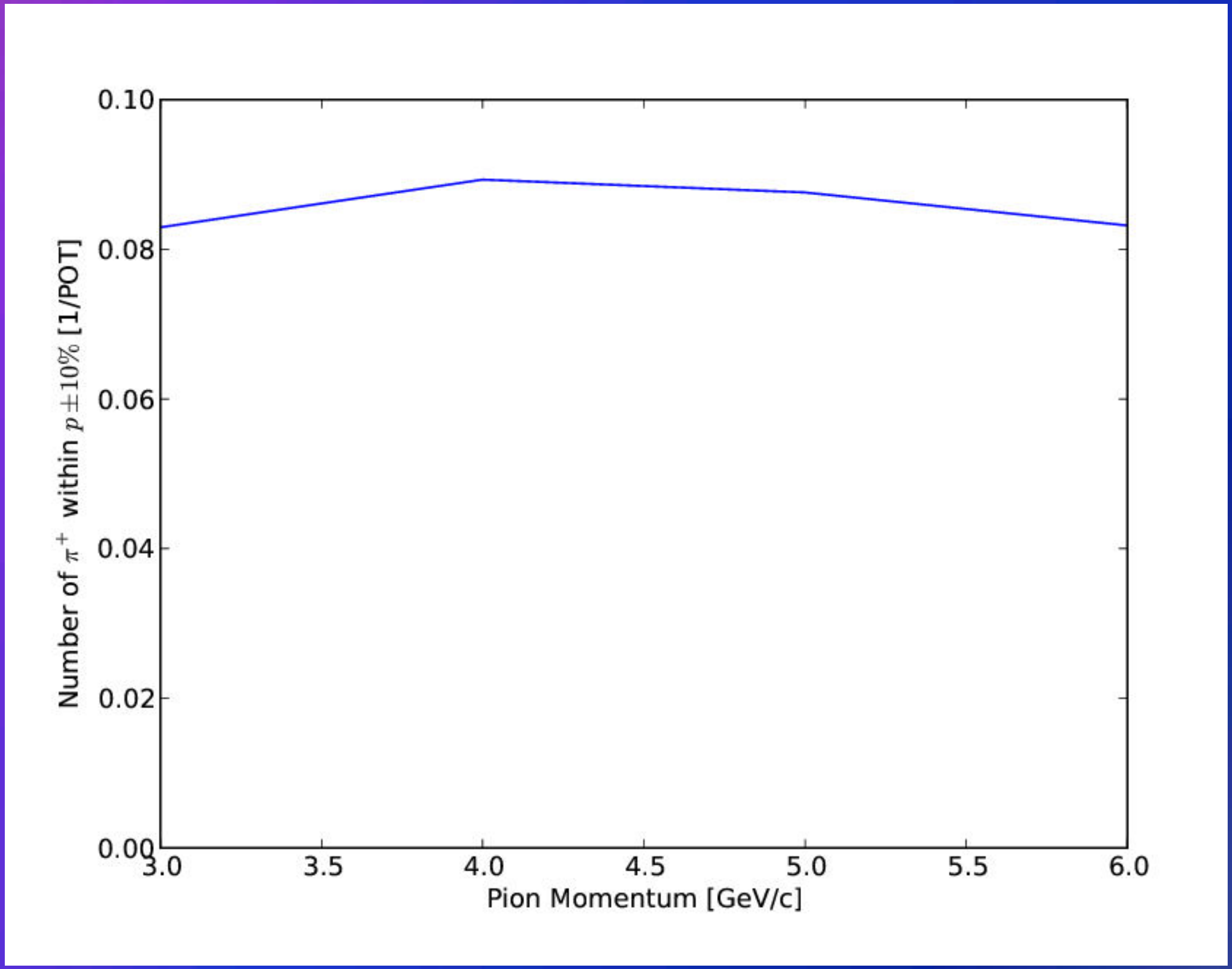
Chris Tunnell
Oxford



Number of useful muon decays

Accelerator

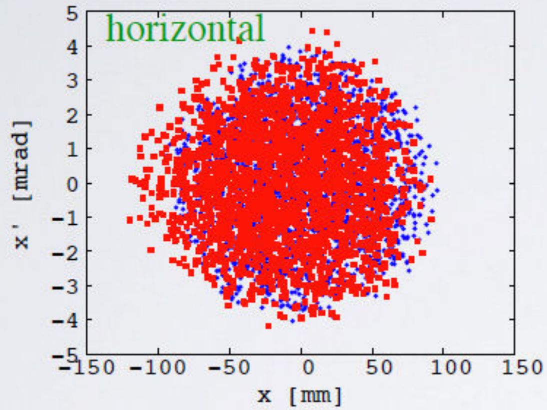
π collection
 # within p ± 10%

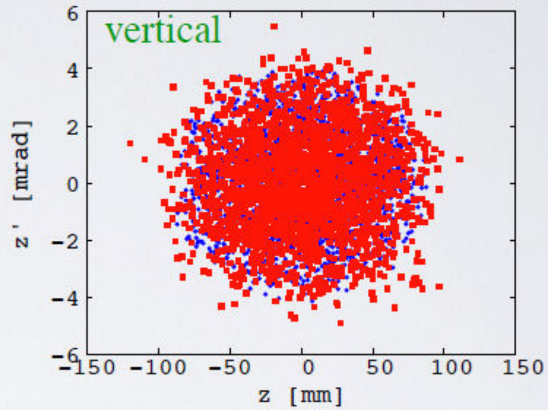


Retune line
(with some loss in efficiency)
to cover $0.3<E_\nu<4$ GeV
&
Resultant extension in L/E
X2-2.5 from lattice
considerations

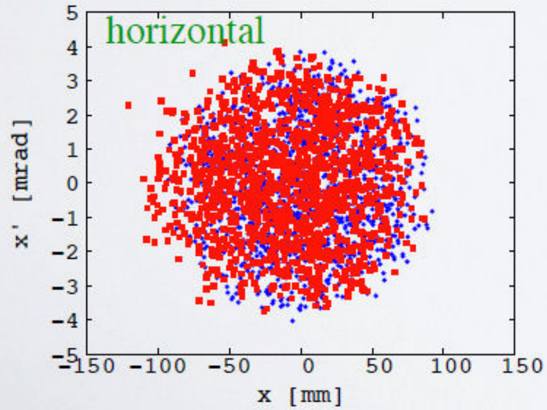
RFFAG Dynamic Aperture

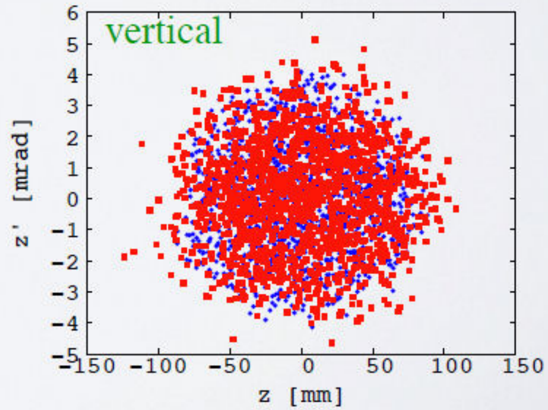
- $\Delta p/p$=+-20%; No particle loss after 60turns





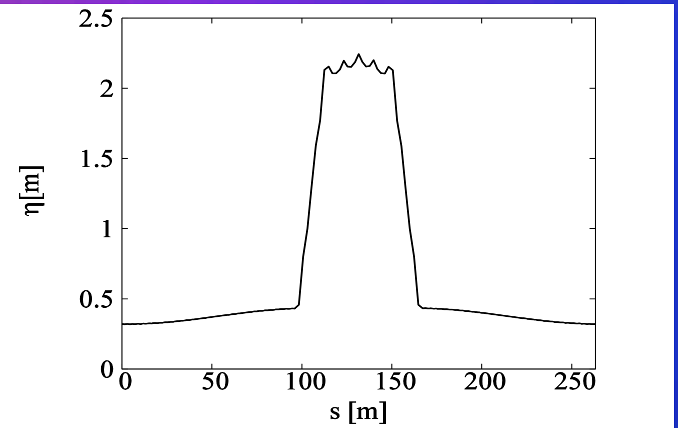
- $\Delta p/p$=+-26%; 0.7% particle loss after 60turns

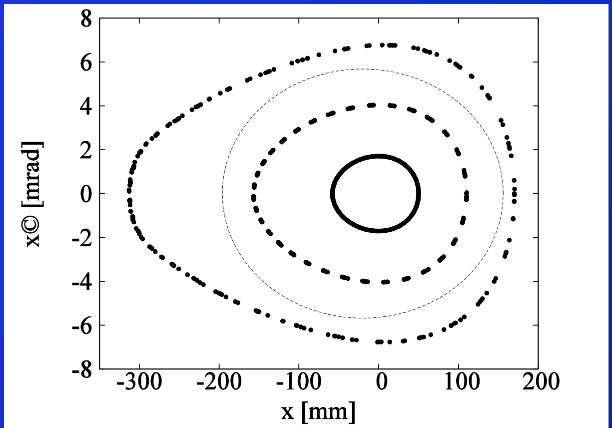


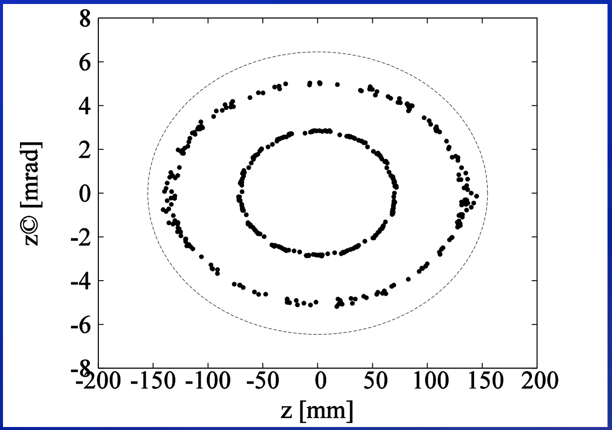


Recent FFAG Decay Ring design

JB Lagrange, Y Mori, J Pasternak, A Sato

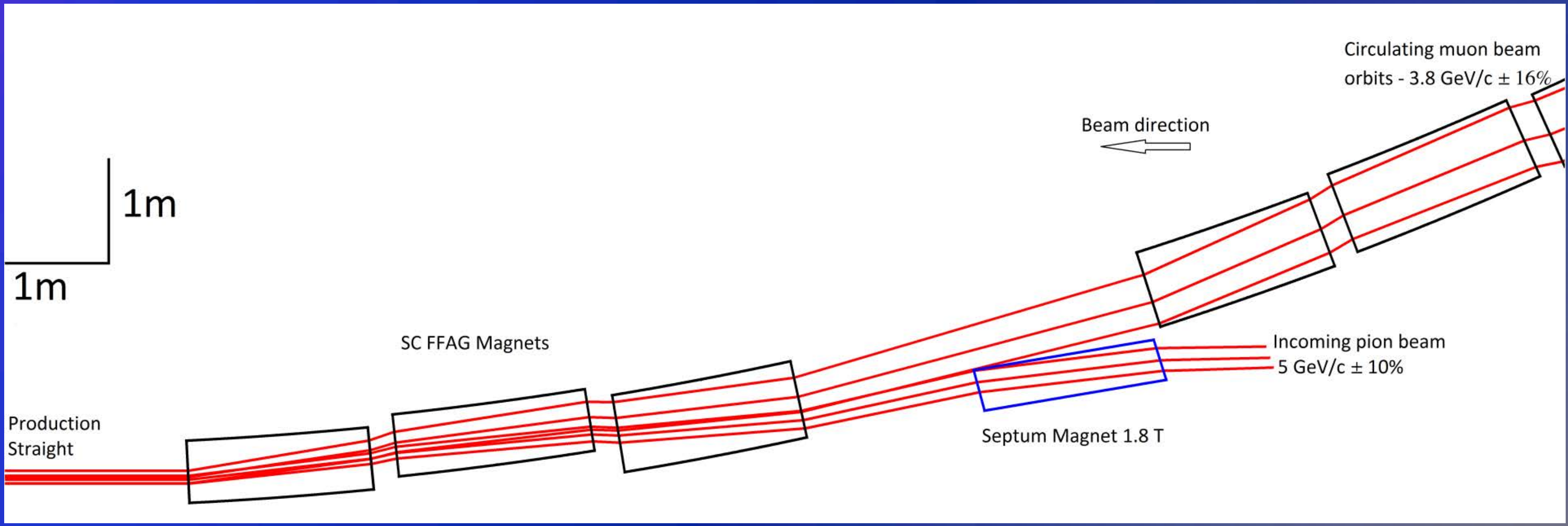






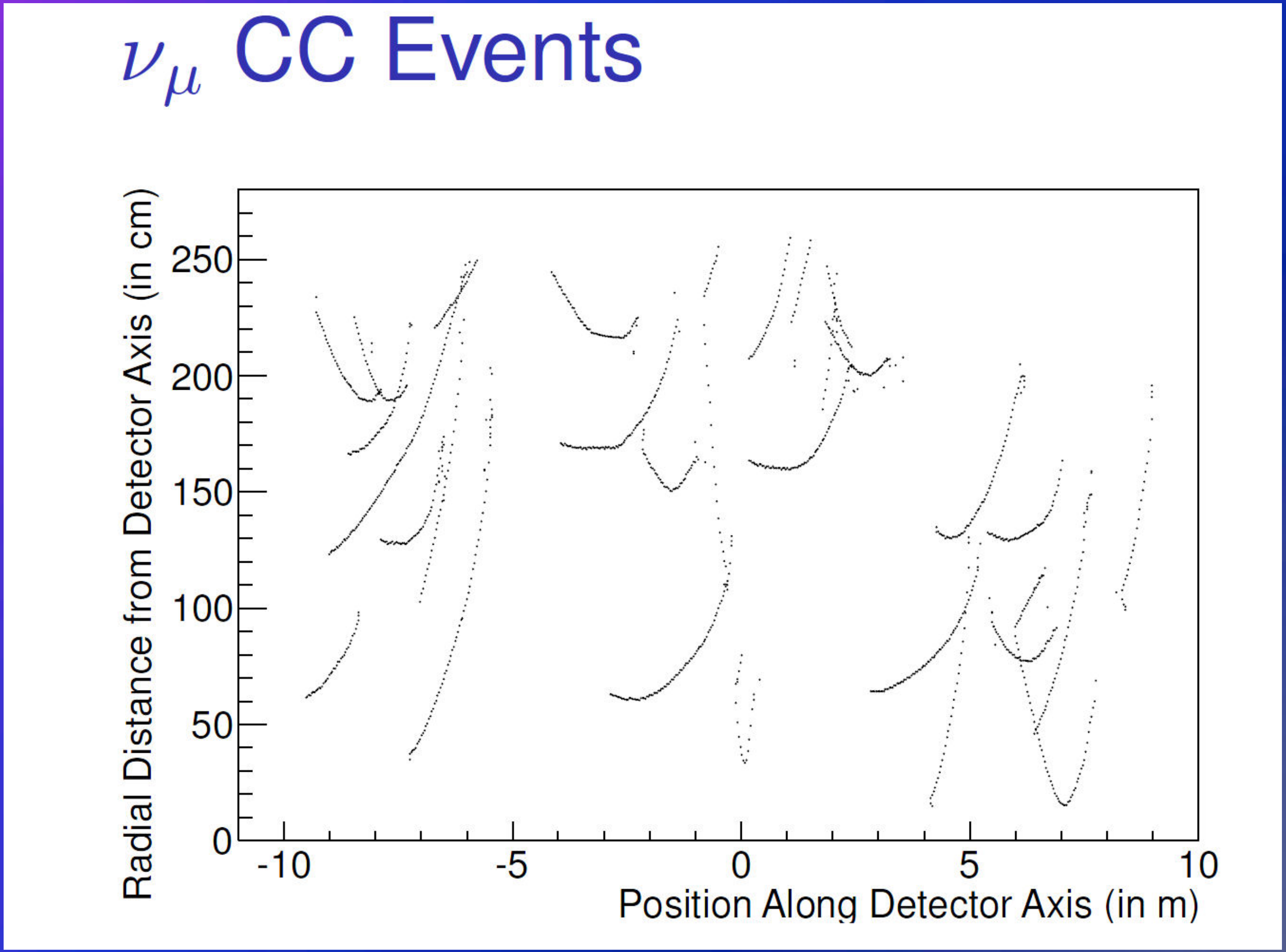
Good dispersion matching (new ring). Horizontal (left) and vertical (right) DA (100 turns).

Preliminary stochastic injection geometry



Detector Issues

Event Candidates in SuperBIND

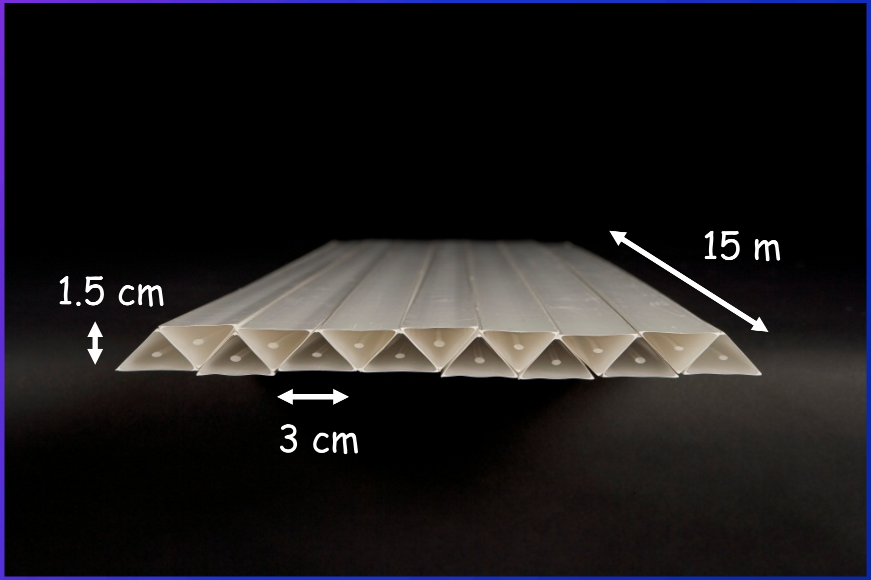


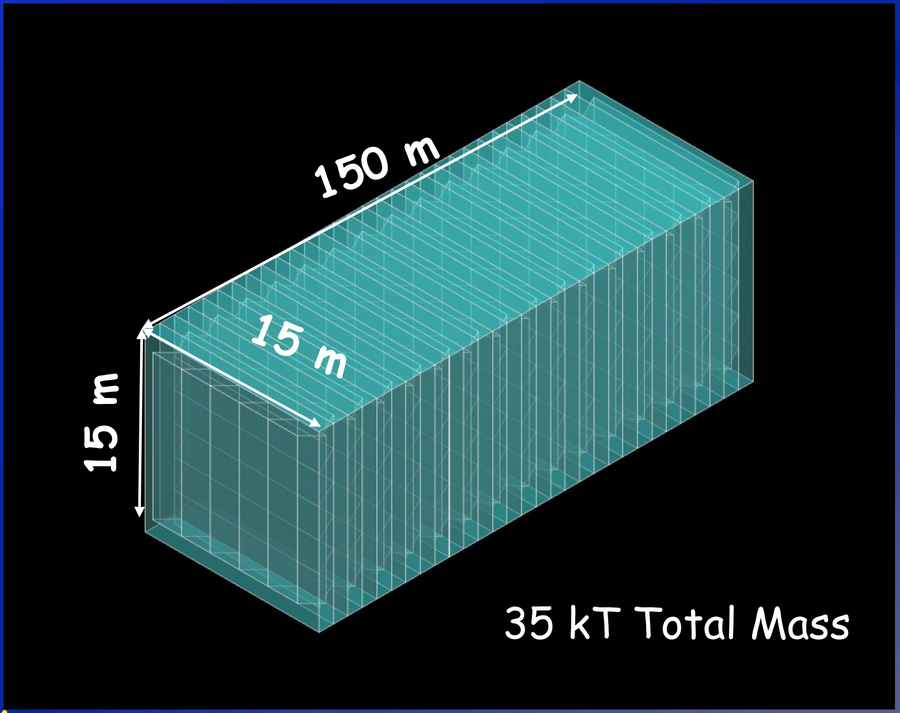
Hits
R vs. Z

Fine-Resolution Totally Active Segmented Detector (IDS-NF)

Simulation of a Totally Active Scintillating Detector (TASD) using Nova and Minerva concepts with Geant4

- 3333 Modules (X and Y plane)
- Each plane contains 1000 slabs
- Total: 6.7M channels



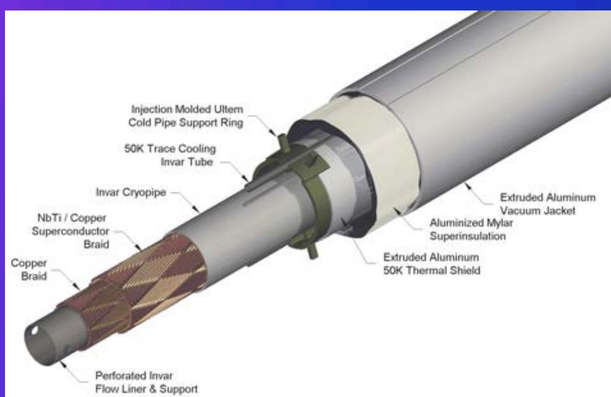


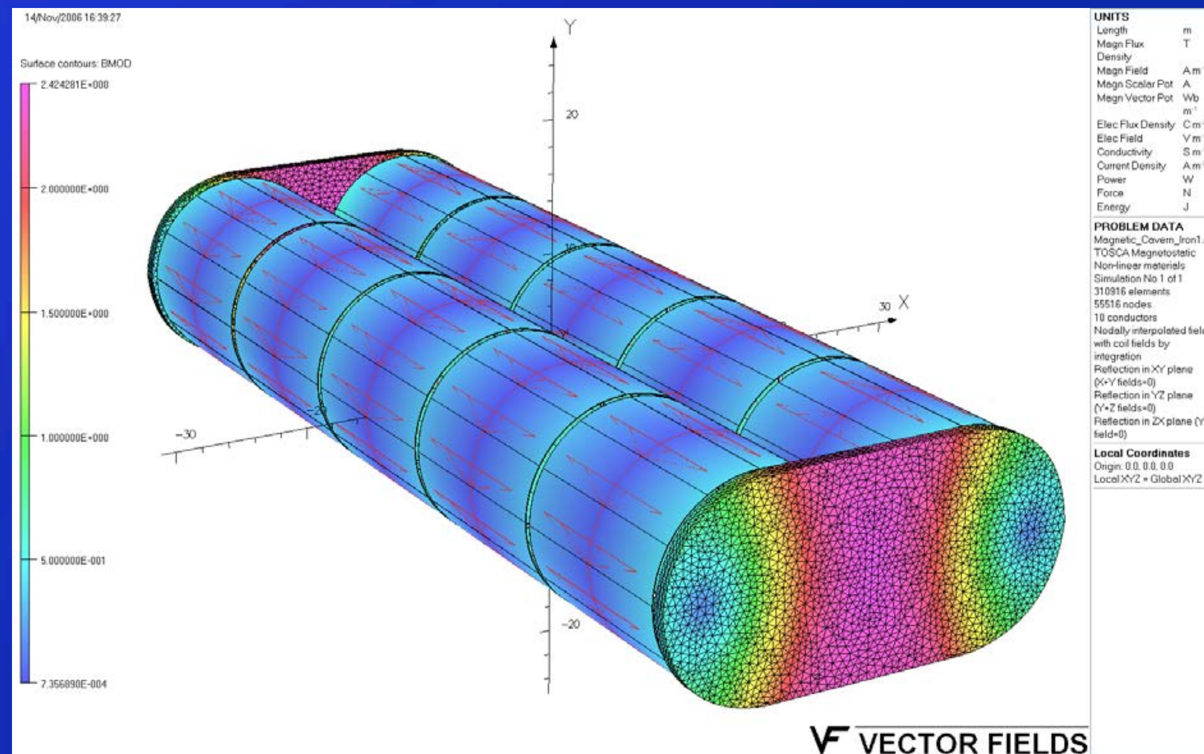
- **Momenta between 100 MeV/c to 15 GeV/c**
- **Magnetic field considered: 0.5 T**
- **Reconstructed position resolution ~ 4.5 mm**

B = 0.5T

Magnet- Concept for IDS-NF

- VLHC SC Transmission Line
  - Technically proven
  - Affordable



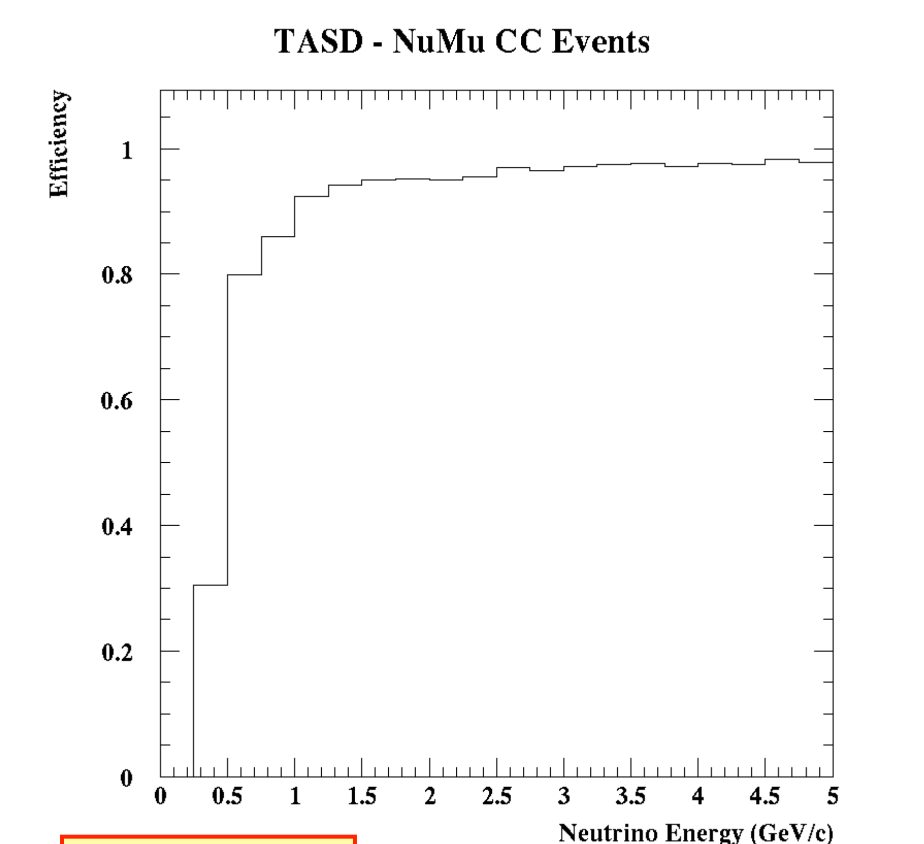


R&D to support concept
Has not been funded

1 m iron wall thickness.
~2.4 T peak field in the iron.
Good field uniformity

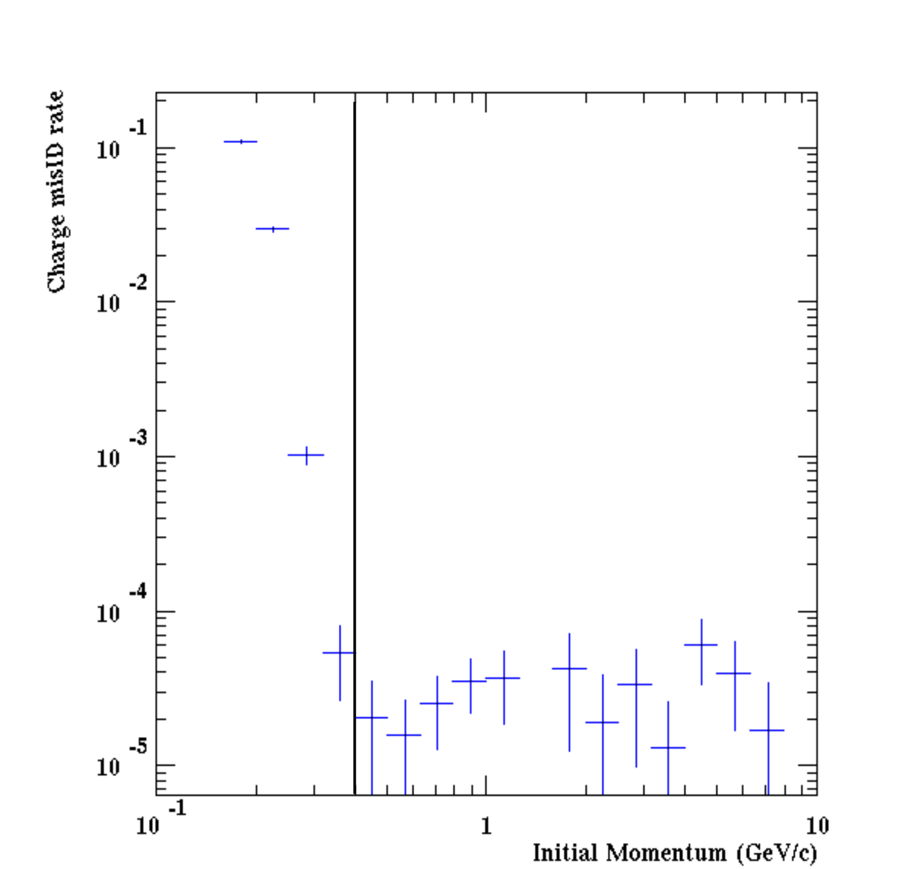
TASD Performance

ν Event Reconstruction ε



Excellent σ_E

Muon charge mis-ID rate



Detector Options

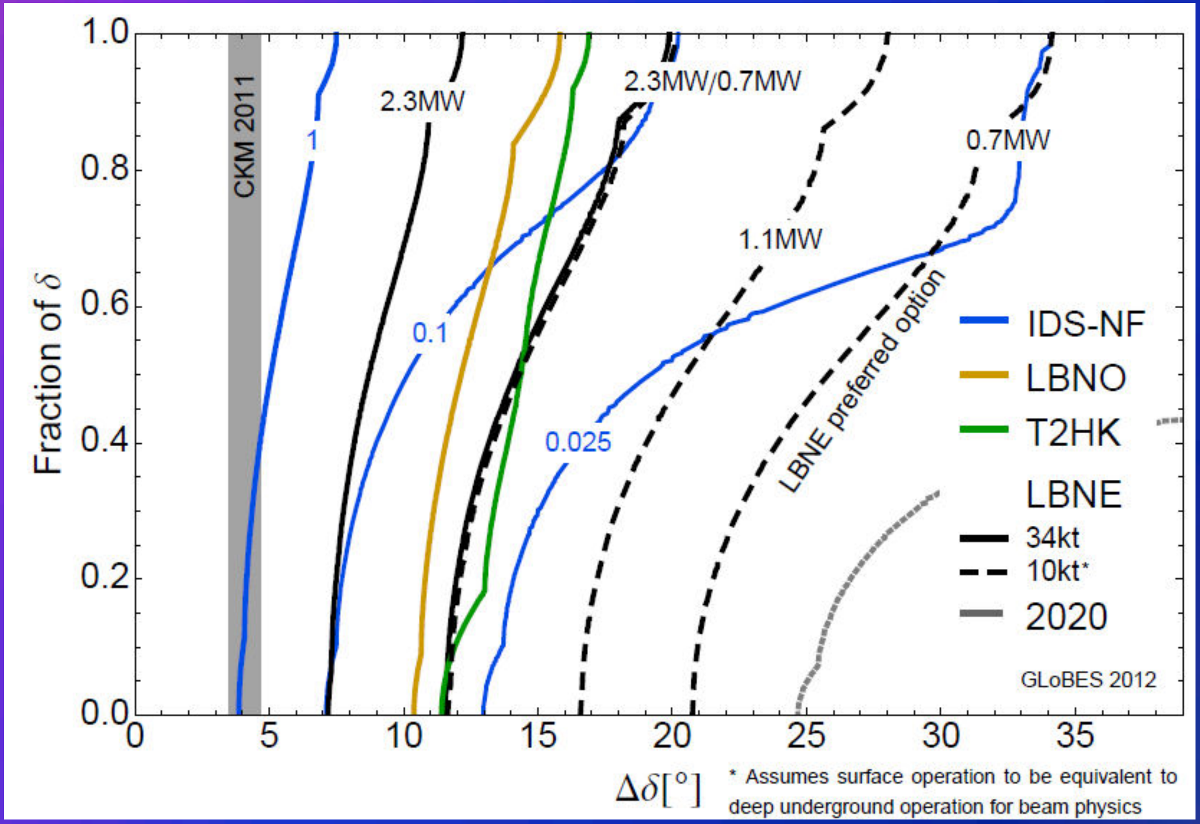
Technology check List

	Fid Volume	B	Recon	Costing Model
SuperBIND	☑	☑	☑	☑
Mag-TASD	☑	☑	☑	☑
Mag-LAr	☑	☑	☑	☑

☑	Yes - OK
☑	Maybe
☑	Not Yet

NF Physics & 3+n Models

NF Upgrade path



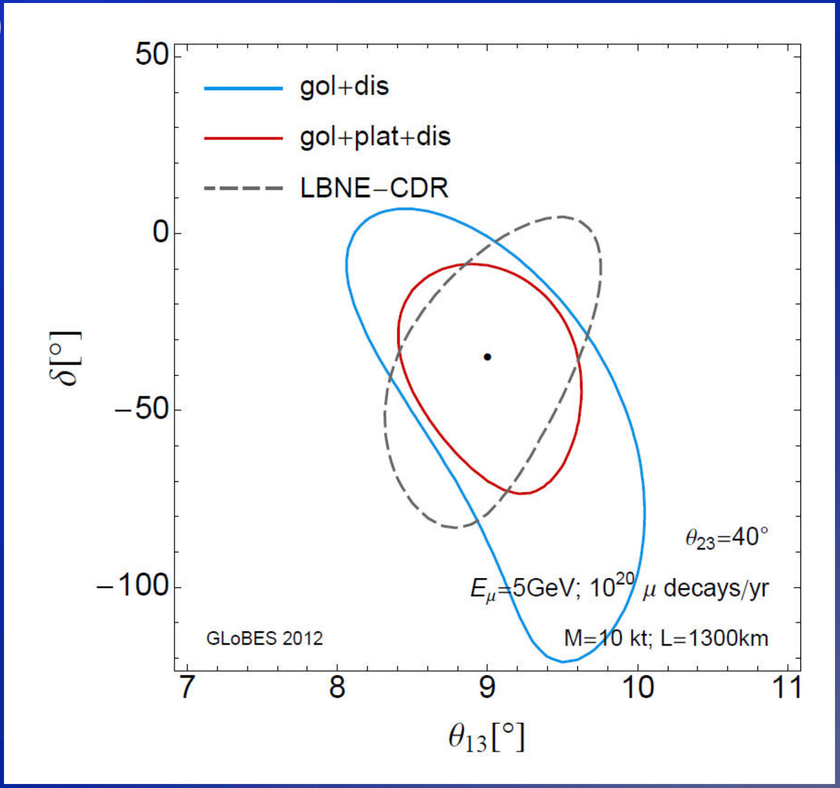
* Assumes surface operation to be equivalent to deep underground operation for beam physics

P. Coloma, P.Huber, J. Kopp, W. Winter, in preparation

- 2020 – T2K, NOνA and Daya Bay
- LBNE – 1300 km, 34 kt
  - 0.7MW, 2 × 10^8 s (10 yrs)
- LBNO – 2300 km, 100 kt
  - 0.8MW, 1 × 10^8 s (10 yrs)
- T2HK – 295 km, 560 kt
  - 0.7MW, 1.2×10^8 s (10 yrs)
- 0.025 IDS-NF
  - 700kW (5 yrs)
  - no cooling
  - 2 × 10^8 s running time
  - 10 kt detector
  - Still Very Expensive
    - LBNE (10kt, surface)

Think even smaller (cheaper)

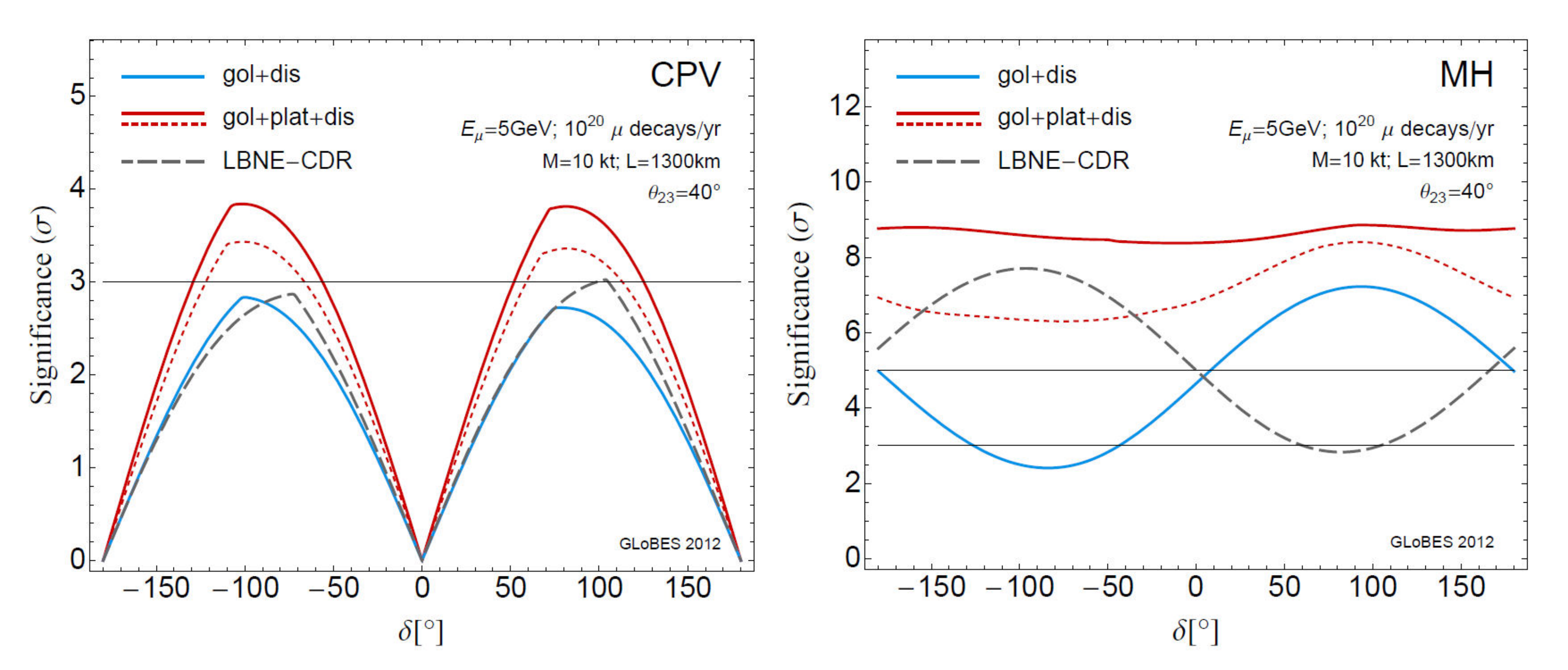
- Low energy Low luminosity NF (L3NF)
  - Add platinum channel (ν_e appearance)
    - Need excellent charge ID
  - E_μ of 5 Gev
  - L = 1300 km
- Specifics
  - 700 kW on target
  - 2 X 10^7 sec/yr.
  - No cooling
- 1% of baseline NF:
  - 10^{20} useful μ decays/yr.
  - 10 kT of Magnetized LAr
    - Underground



Christensen, Coloma and Huber
arXiv: 1301.7727

Confidence region in the θ_{13} – δ plane for a particular point in the parameter space, at 1σ

L3NF: CPV and MH



What is still so compelling about the NF is how robust its physics case is. Even at only 1% of the baseline Flux X (Fiducial Mass), it still can do world-class physics. It also presents a tenable upgrade path to explore with much greater precision the νSM and to look beyond, NSIs, heavy ν……?.

3 + 3 Model

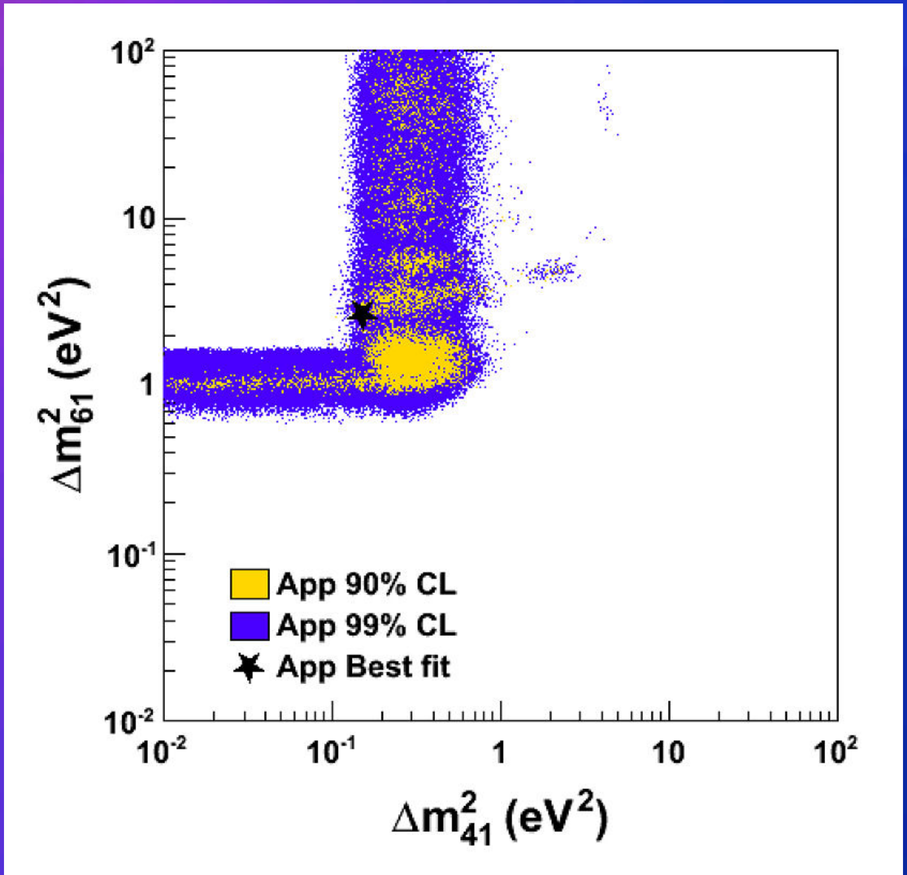
	χ^2_{min} (dof)	χ^2_{null} (dof)	P_{best}	P_{null}	χ^2_{PG} (dof)	PG (%)
3+1						
All	233.9 (237)	286.5 (240)	55%	2.1%	54.0 (24)	0.043%
App	87.8 (87)	147.3 (90)	46%	0.013%	14.1 (9)	12%
Dis	128.2 (147)	139.3 (150)	87%	72%	22.1 (19)	28%
ν	123.5 (120)	133.4 (123)	39%	25%	26.6 (14)	2.2%
$\overline{\nu}$	94.8 (114)	153.1 (117)	90%	1.4%	11.8 (7)	11%
App vs. Dis	-	-	-	-	17.8 (2)	0.013%
ν vs. $\overline{\nu}$	-	-	-	-	15.6 (3)	0.14%
3+2						
All	221.5 (233)	286.5 (240)	69%	2.1%	63.8 (52)	13%
App	75.0 (85)	147.3 (90)	77%	0.013%	16.3 (25)	90%
Dis	122.6 (144)	139.3 (150)	90%	72%	23.6 (23)	43%
ν	116.8 (116)	133.4 (123)	77%	25%	35.0 (29)	21%
$\overline{\nu}$	90.8 (110)	153.1 (117)	90%	1.4%	15.0 (16)	53%
App vs. Dis	-	-	-	-	23.9 (4)	0.0082%
ν vs. $\overline{\nu}$	-	-	-	-	13.9 (7)	5.3%
3+3						
All	218.2 (228)	286.5 (240)	67%	2.1%	68.9 (85)	90%
App	70.8 (81)	147.3 (90)	78%	0.013%	17.6 (45)	100%
Dis	120.3 (141)	139.3 (150)	90%	72%	24.1 (34)	90%
ν	116.7 (111)	133.4 (123)	34%	25%	39.5 (46)	74%
$\overline{\nu}$	90.6 (105)	153 (117)	84%	1.4%	18.5 (27)	89%
App vs. Dis	-	-	-	-	28.3 (6)	0.0081%
ν vs. $\overline{\nu}$	-	-	-	-	110.9 (12)	53%

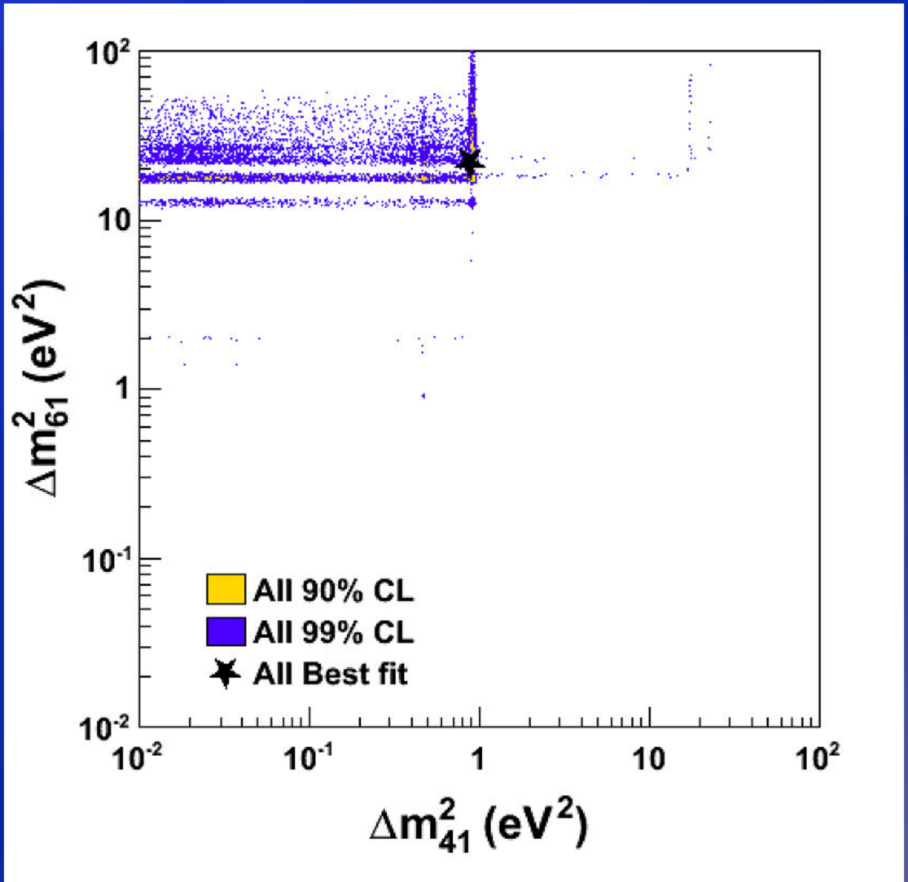
- *A 3+3 model has recently been shown to better fit all available data*

Tag	Section	Process	ν vs. $\bar{\nu}$	App vs. Dis
LSND	3.2.1	$\bar{\nu}_\mu \to \bar{\nu}_e$	$\bar{\nu}$	App
KARMEN	3.2.1	$\bar{\nu}_\mu \to \bar{\nu}_e$	$\bar{\nu}$	App
KARMEN/LSND(xsec)	3.2.1	$\nu_e \to \nu_e$	ν	Dis
BNB-MB(νapp)	3.2.2	$\nu_\mu \to \nu_e$	ν	App
BNB-MB($\bar{\nu}$app)	3.2.2	$\bar{\nu}_\mu \to \bar{\nu}_e$	$\bar{\nu}$	App
NuMI-MB(νapp)	3.2.2	$\nu_\mu \to \nu_e$	ν	App
BNB-MB(νdis)	3.2.2	$\nu_\mu \to \nu_\mu$	ν	Dis
NOMAD	3.2.3	$\nu_\mu \to \nu_e$	ν	App
CCFR84	3.2.3	$\nu_\mu \to \nu_\mu$	ν	Dis
CDHS	3.2.3	$\nu_\mu \to \nu_\mu$	ν	Dis
Bugey	3.2.4	$\bar{\nu}_e \to \bar{\nu}_e$	$\bar{\nu}$	Dis
Gallium	3.2.4	$\nu_e \to \nu_e$	ν	Dis
MINOS-CC	3.2.5	$\bar{\nu}_\mu \to \bar{\nu}_\mu$	$\bar{\nu}$	Dis
ATM	3.2.5	$\nu_\mu \to \nu_\mu$	ν	Dis

J.M. Conrad, C.M. Ignarra, G. Karagiorgi, M.H. Shaevitz, J. Spitz (arXiv:1207.4765v1)

3 + 3 Model II



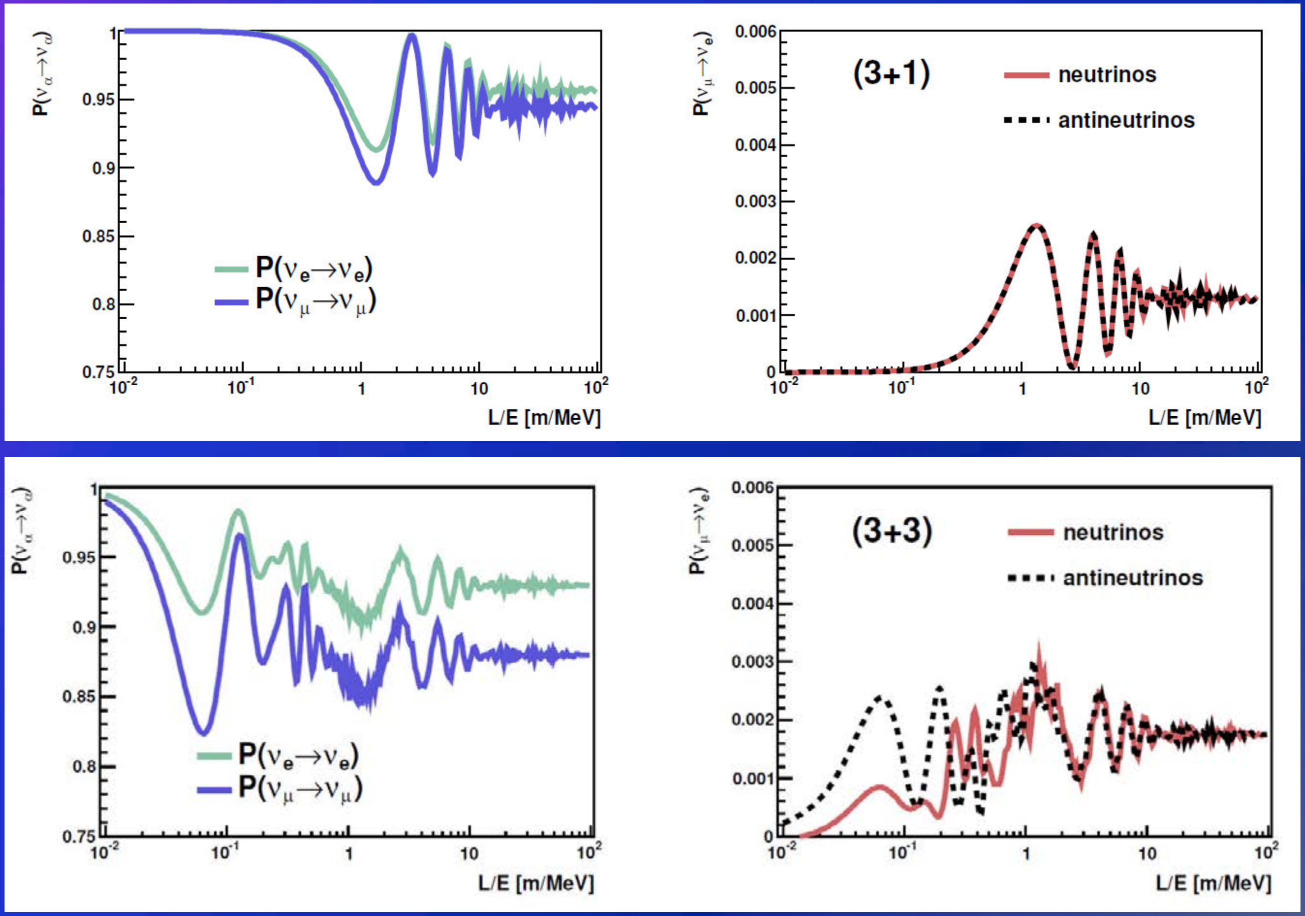


Appearance Data

All Data

Lesson: Have access to as many channels as possible and cover as much of the parameter space as possible

L/E dependence



Very different L/E dependencies for different models
Experiments covering a wide range of L/E regions are required.

S:B for Appearance Channel
Past and Future(?)

Experiment	S:B
LSND	2:1
MiniBooNE	1:1 → 1:2
ICARUS/NESSiE	≈1.5:1 / 1:4
LAr-LAr	1:4
K^+ DAR	≈4:1
LSND Reloaded	5:1
oscSNS	3:1
nuSTORM	11:1 → 20:1

- Note: There are a number of experiments with megaCi to petaCi sources next to large detectors that have an exquisite signature of steriles (# evts/unit length displays oscillatory behavior in large detector) and have large effective S:B
  - SNO+Cr, Ce-Land, LENS, Borexino, Daya Bay
  - IsoDAR
  - A number of very-short baseline reactor experiments

Costing

Association for the Advancement of Costing Engineering (AACE)

Bob O'Sullivan

Developing the Cost Range

	Primary Characteristic	Secondary Characteristic		
ESTIMATE CLASS	**DEGREE OF PROJECT DEFINITION** Expressed as % of complete definition	**END USAGE** Typical purpose of estimate	**METHODOLOGY** Typical estimating method	**EXPECTED ACCURACY RANGE** Typical variation in low and high ranges [a]
Class 5	0% to 2%	Concept screening	Capacity factored, parametric models, judgment, or analogy	L: -20% to -50% H: +30% to +100%
Class 4	1% to 15%	Study or feasibility	Equipment factored or parametric models	L: -15% to -30% H: +20% to +50%
Class 3	10% to 40%	Budget authorization or control	Semi-detailed unit costs with assembly level line items	L: -10% to -20% H: +10% to +30%
Class 2	30% to 70%	Control or bid/tender	Detailed unit cost with forced detailed take-off	L: -5% to -15% H: +5% to +20%
Class 1	70% to 100%	Check estimate or bid/tender	Detailed unit cost with detailed take-off	L: -3% to -10% H: +3% to +15%

LBNE CD-1 Director's Review - 25-27 September 2012 16

Example: LBNE

Elements of the Estimate - TPC

- Total Project Cost (TPC)
  - TPC includes the sum of all Estimate Elements,
  - The TPC provides 40% Contingency, with an expected Confidence Level of 95% (Project Director's Assessment)

130 L.B.N.E.	Cost to Date (in M)	Estimate to Complete (ETC) (in M)	Bottoms Up Estimate Uncertainity Contingency (in M)	Risk Based Contingency (in M)	Top Down Contingency (in M)	TPC (in M)
	thru 6/2012	beyond 6/2012				
130.01 Project Office	$7.0	$50.0	$8.9	$7.2	$30.0	$103.1
130.02 Beamline	$7.4	$121.9	$33.5	$1.8		$164.7
130.03 Near Detector	$4.6	$7.3	$1.3	$9.4		$22.6
130.04 Water Cherenkov Detector	$11.2	$0.0				$11.2
130.05 LAr Far Detector	$7.8	$173.6	$61.9	$9.9		$253.1
130.06 LBNE Conventional Facilities	$6.9	$234.3	$57.8	$13.8		$312.8
Grand Total	**$44.8**	**$587.1**	**$163.7**	**$42.1**	**$30.0**	**$867.4**
% Contingency			**28%**	**7%**	**5%**	**40%**

LBNE cost range

Calculating the Cost Range

- Actuals thru June 2012 were then added to Cost Range for Estimate to Complete to determine the TPC Cost Range
- Per AACE, following this approach provides a 95% confidence level that the actual costs will fall below the upper end of the cost range.

130 L.B.N.E.	Cost Range Estimate to Complete (in M)		Cost to Date (in M)	TPC Cost Range (in M)	
	minus (-)	plus (+)	thru 6/2012	minus (-)	plus (+)
130.01 Project Office	$75.2	$106.2	$7.0	$82.2	$113.2
130.02 Beamline	$129.0	$164.9	$7.4	$136.4	$172.3
130.03 Near Detector	$13.1	$18.5	$4.6	$17.7	$23.1
130.04 Water Cherenkov Detector	$0.0	$0.0	$11.2	$11.2	$11.2
130.05 LAr Far Detector	$184.9	$271.9	$7.8	$192.6	$279.6
130.06 LBNE Conventional Facilities	$239.8	$338.5	$6.9	$246.6	$345.4
Grand Total	**$642.0**	**$899.9**	**$44.8**	**$686.8**	**$944.7**
% Contingency				**9%**	**53%**

Top of Range provides for 53% contingency above Base Estimate